

Future Opportunities at an Electron-Ion Collider

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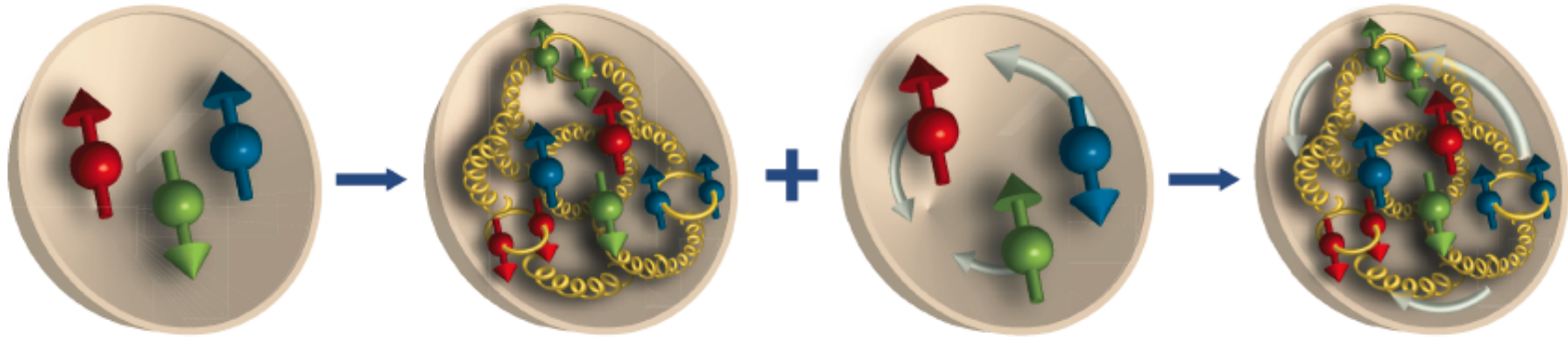
BROOKHAVEN
NATIONAL LABORATORY



Exploring the Glue that Binds Us All

- Questions at the next QCD frontier
 - How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
 - Where does the saturation of gluon densities set in?
 - How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?
- An Electron-Ion Collider
 - Electron beams for precision measurements
 - Polarized nucleon beams
 - Heavy ion beams of different species
 - Kinematic reach into the gluon dominated regime
 - Dedicated hermetic detector setup

The Structure of the Nucleon

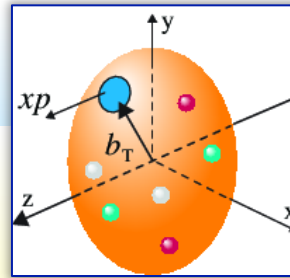


- What is the dynamical origin of sea quarks and gluons inside the proton?
- How does the proton spin originate at the microscopic level?
- How is hadron structure influenced by chiral symmetry and its breaking?
- How does confinement manifest itself in the structure of hadrons?

Partonic Picture of the Nucleon

5D

Wigner distributions
 $W(x, b \downarrow T, k \downarrow T)$



$$\int \int d^2b \int d^2k W(x, b \downarrow T, k \downarrow T)$$

3D

transverse momentum

$$f(x, k \downarrow T)$$

impact parameter

$$f(x, b \downarrow T)$$

Fourier trans.

$$b \downarrow T \leftrightarrow \Delta$$

 $t = -\Delta^2$

$$H(x, 0, t)$$

generalized parton distributions

$$\xi = 0$$

$$H(x, \xi, t)$$

$$\int \int d^2k \int d^2b f(x, k \downarrow T, b \downarrow T)$$

$$f(x)$$

parton densities

1D

$$\int dx$$

$$F_1(t)$$

form factors

$$\int dx x^{n-1}$$

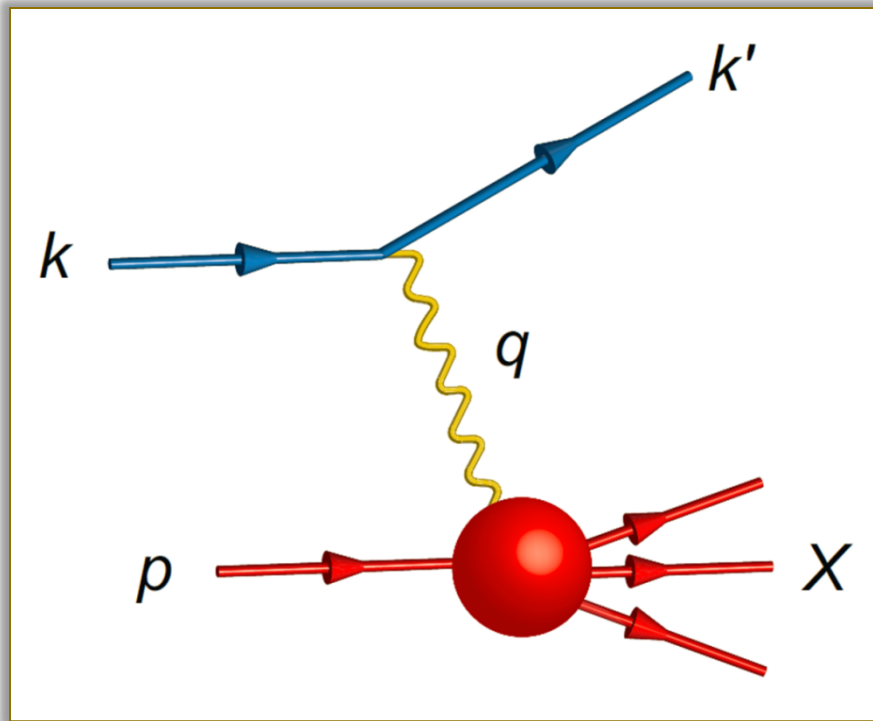
$$A_{n,0}(t) + \xi^2 A_{n,2}(t) + \dots$$

generalized form factors

TMDs: confined partonic motion inside the nucleon

GPDs: spatial imaging of quarks and gluons

Deep Inelastic Scattering



Lorentz invariants

$$s = (p + k)^2 = 4 \cdot E_e \cdot E_p$$

$$Q^2 = -q^2 = -(k - k')^2$$

$$x_B = Q^2 / (2 \cdot p \cdot q)$$

$$y = q \cdot p / k \cdot p$$

$$Q^2 = x \cdot y \cdot s$$

In the collider frame

$$E_e' = E_e \cdot (1 - y) + Q^2 / (4 \cdot E_e)$$

Other variables $W^2 = (p + q)^2 = Q^2 \cdot (1 - 1/x)$

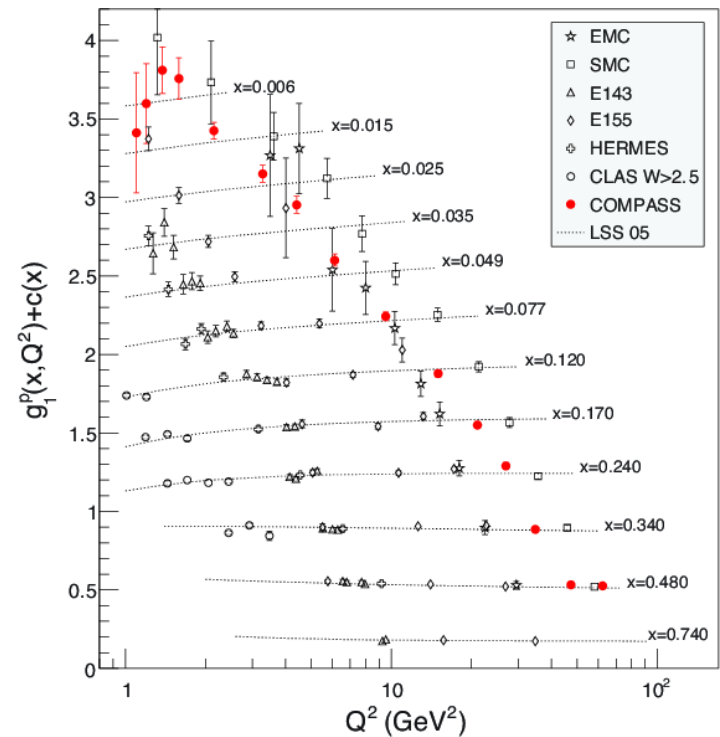
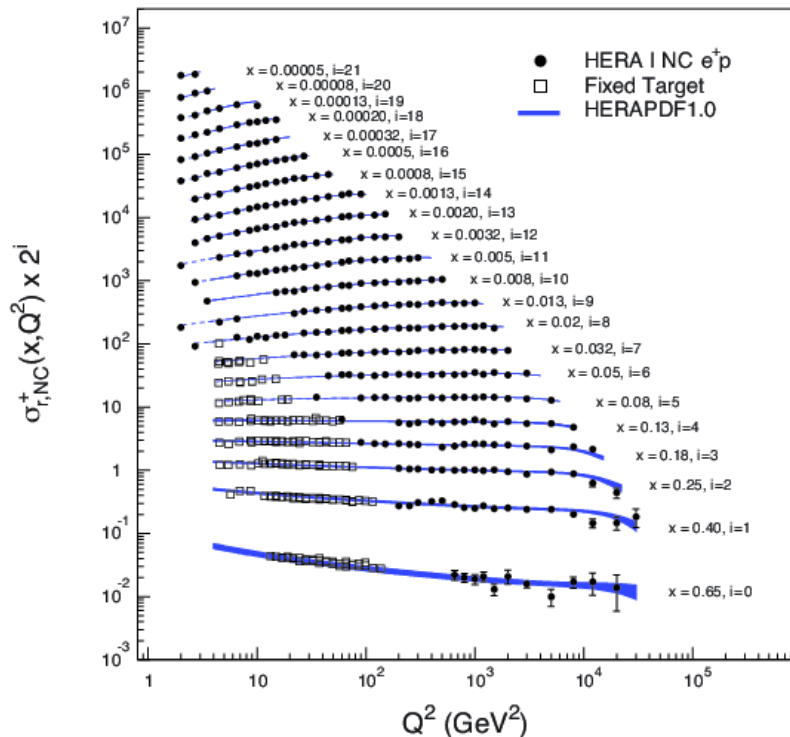
$$v = q \cdot p / M = y \cdot s / (2M)$$

Structure Functions

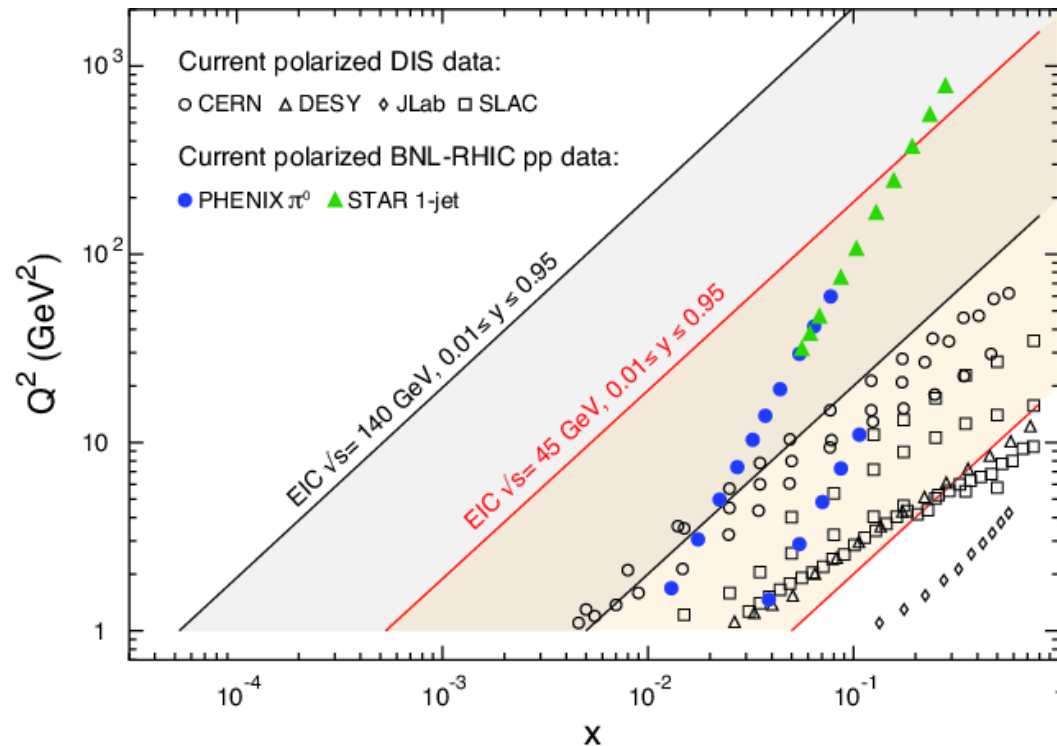
$$d^2\sigma/dxdQ^2 = 4\pi\alpha^2 / xQ^4 [(1-y+y^2/2)F_2(x,Q^2) - y^2(x/Q^2)L - (x/Q^2)H(1-y)]$$

$$F_2(x,Q^2) = x\sum_i e_i^2 q_i(x,Q^2) [q(x,Q^2) + \bar{q}(x,Q^2)]$$

$$F_L(x,Q^2) = x\sum_i e_i^2 q_i(x,Q^2) [\Delta q(x,Q^2) + \Delta \bar{q}(x,Q^2)]$$



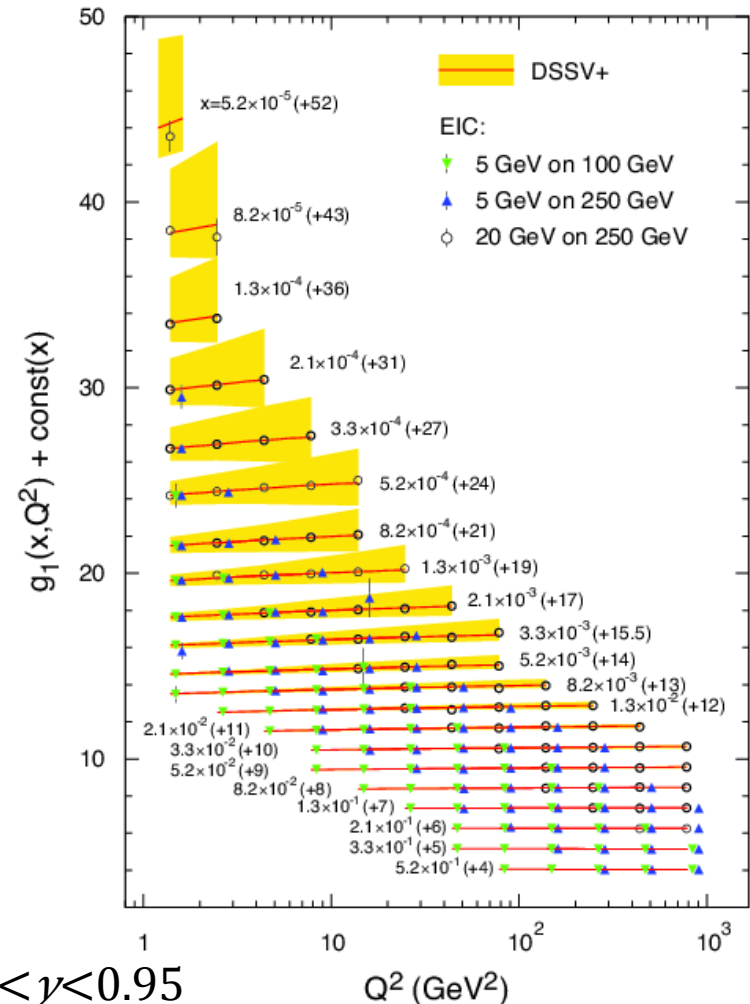
Longitudinal Spin Structure



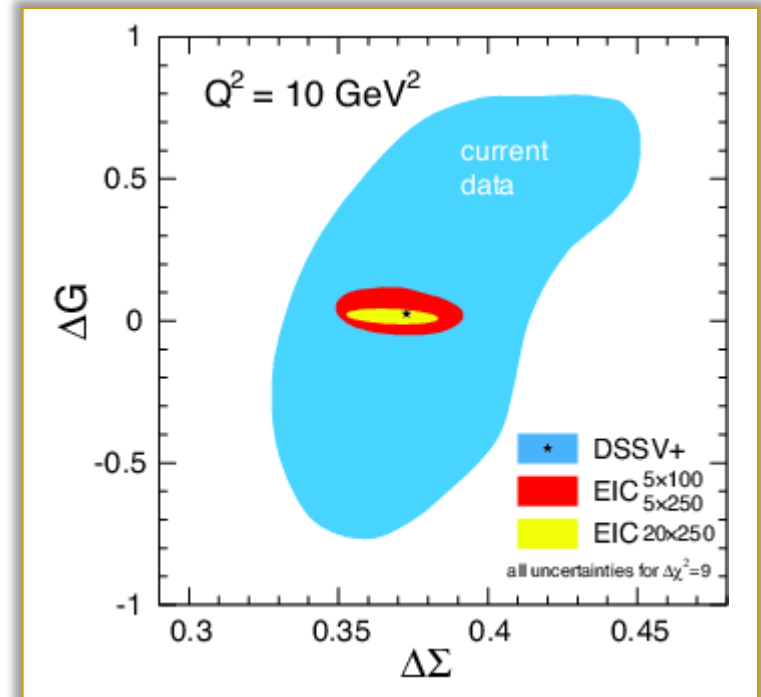
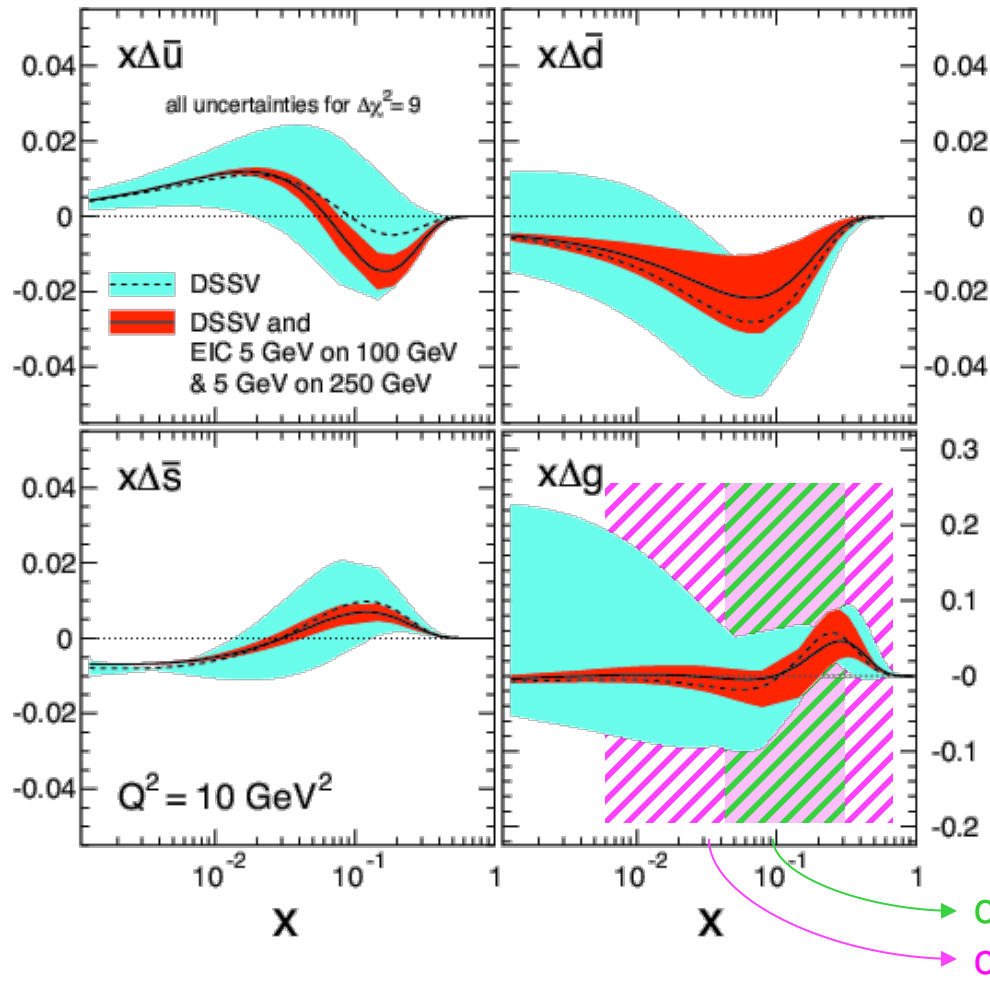
EIC pseudo data based on PEPSI Monte-Carlo

$L \downarrow \text{int} = 10 \text{ fb} \uparrow - 1$

$Q \downarrow \text{min} \uparrow 2 = 1 \text{ GeV} \uparrow 2, W \uparrow 2 > 10 \text{ GeV} \uparrow 2, 0.01 < y < 0.95$

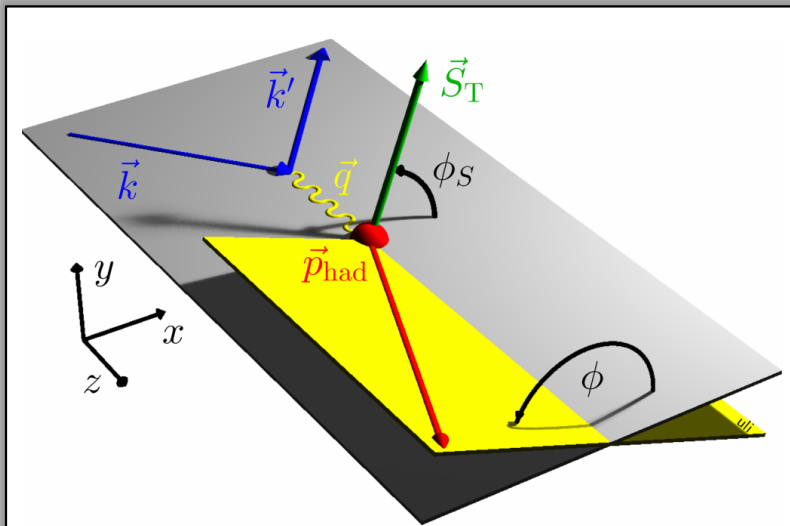


Longitudinal Spin Structure



Unprecedented and
decisive answer to the
partonic polarizations

Semi-inclusive DIS



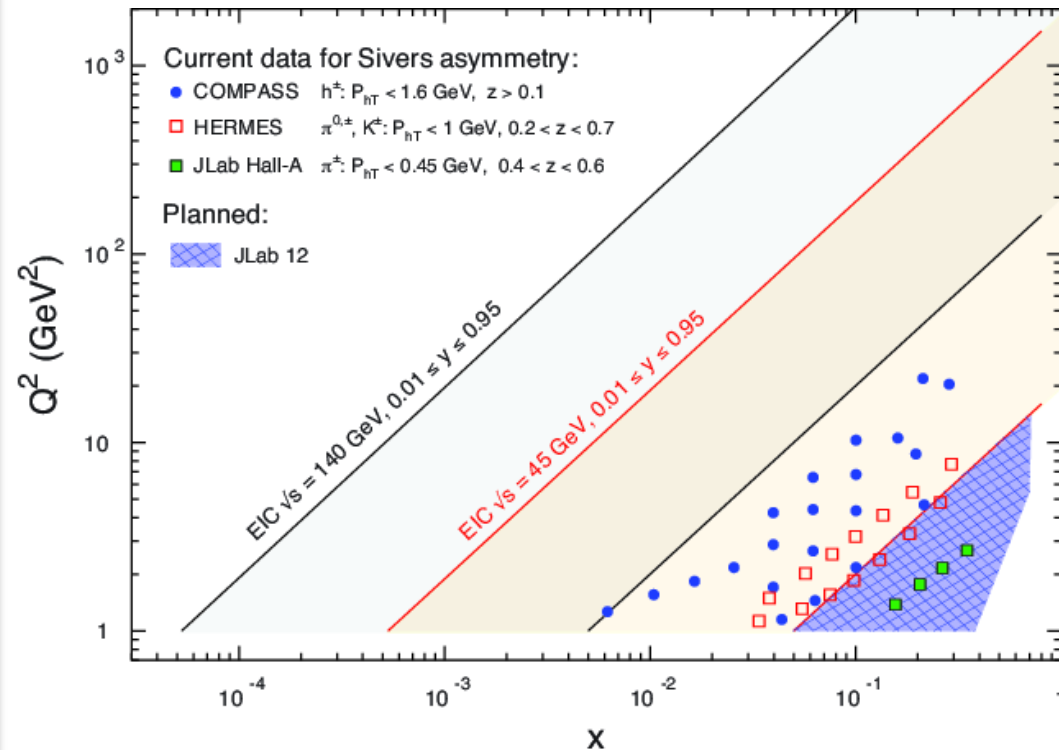
Additional degrees of freedom:

Transverse momentum p_T

Fragmentation $z = P_{h \cdot P} / q \cdot P$

Azimuthal correlation ϕ, ϕ_S

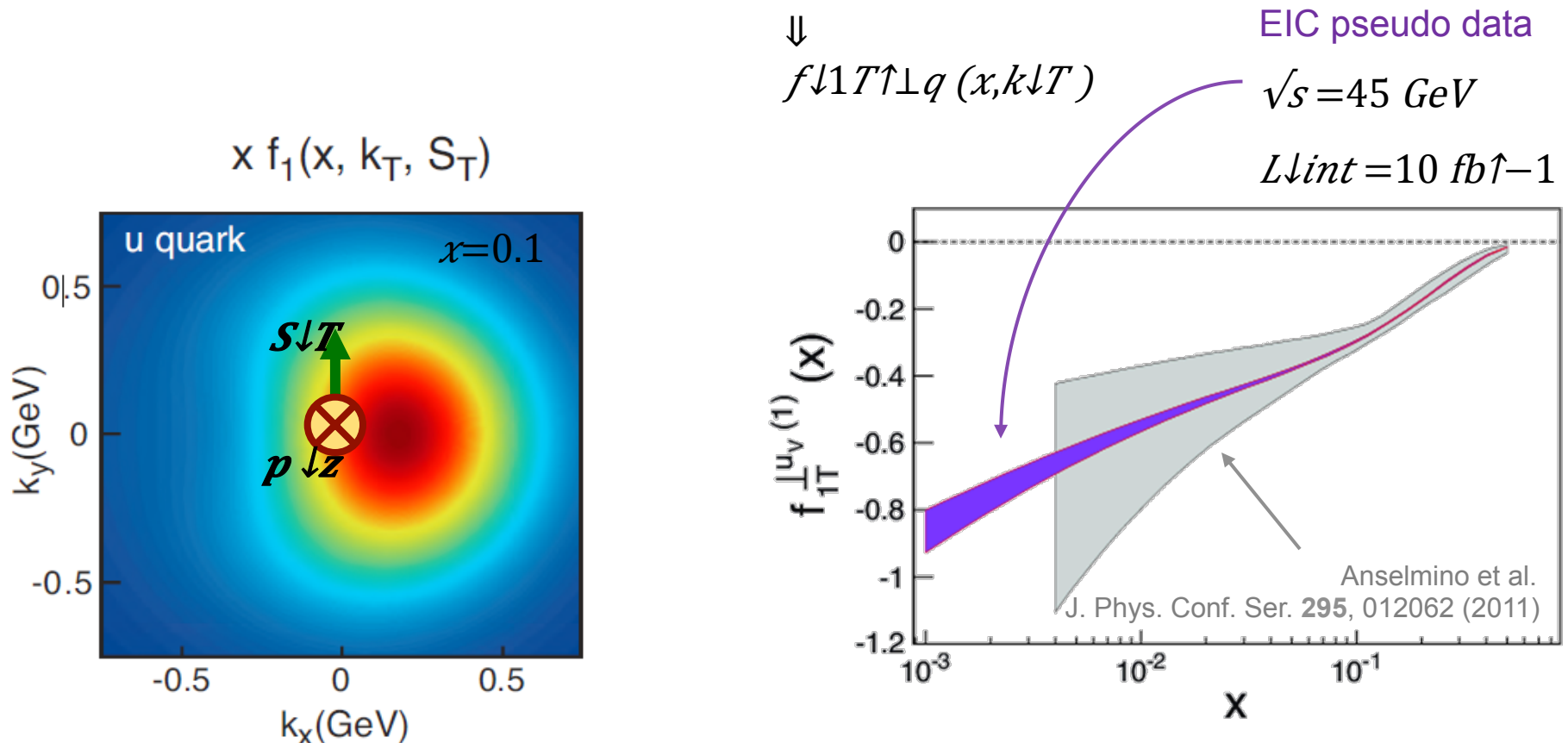
Limited data from fixed target experiments



Go beyond the one-dimensional picture in parton TMD distributions

Quark TMD Distributions

$$d\sigma/dx dy d\phi dz d\phi_S dp_T^2 \propto F_{UU,T} + |S_\perp| |\sin(\phi - \phi_S)| F_{UT,T} \sin(\phi - \phi_S) + \dots$$

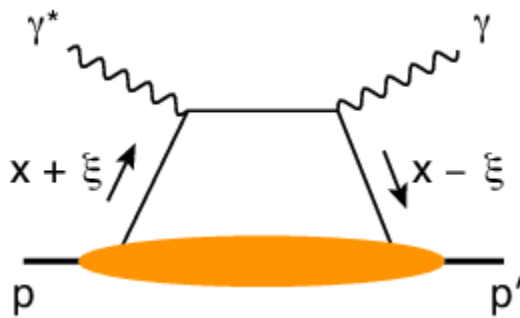


Spatial Imaging of Nucleons

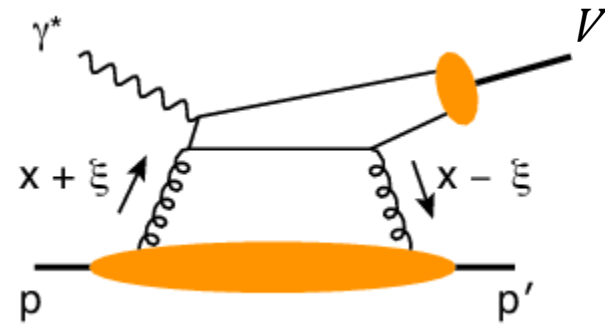
$$f^{\uparrow\uparrow}(x, b \downarrow T) = f(x, b \downarrow T^{\uparrow\downarrow}) + (S \downarrow T \times b \downarrow T)^{\uparrow\downarrow} z / M \partial / \partial b \downarrow T^{\uparrow\downarrow} e(x, b \downarrow T^{\uparrow\downarrow})$$

$$\left. \begin{array}{l} f(x, b \downarrow T^{\uparrow\downarrow}) \\ e(x, b \downarrow T^{\uparrow\downarrow}) \end{array} \right\} \text{Fourier transform of } \left\{ \begin{array}{l} H(x, \xi, t) \\ E(x, \xi, t) \end{array} \right\} \text{ at } \xi=0$$

Exclusive processes to measure generalized parton distribution functions:



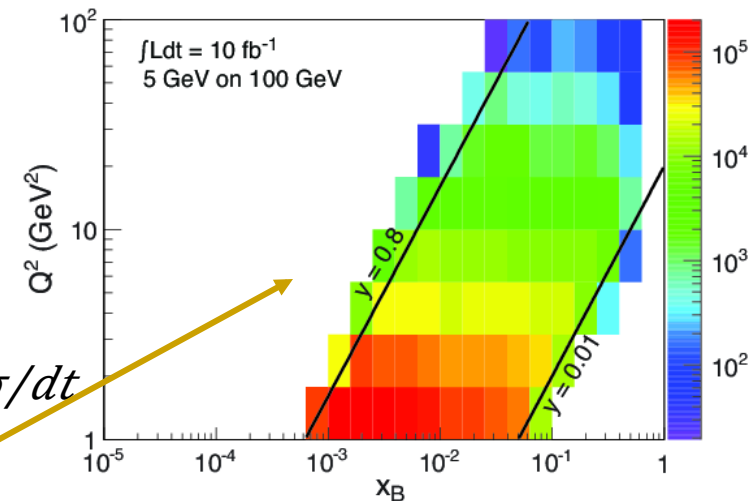
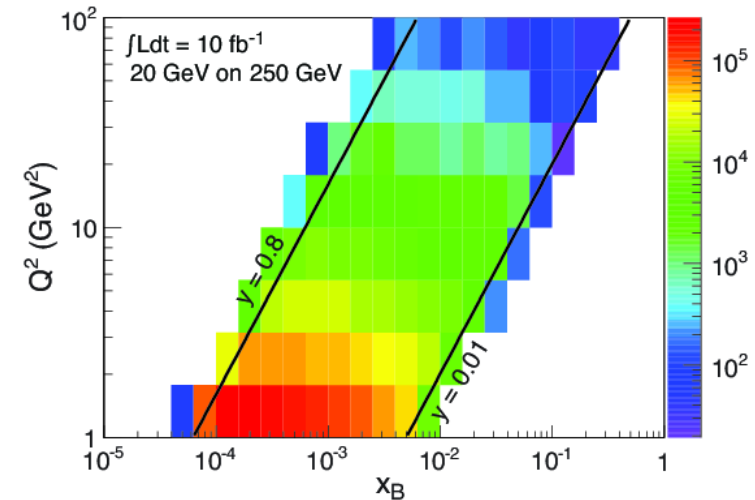
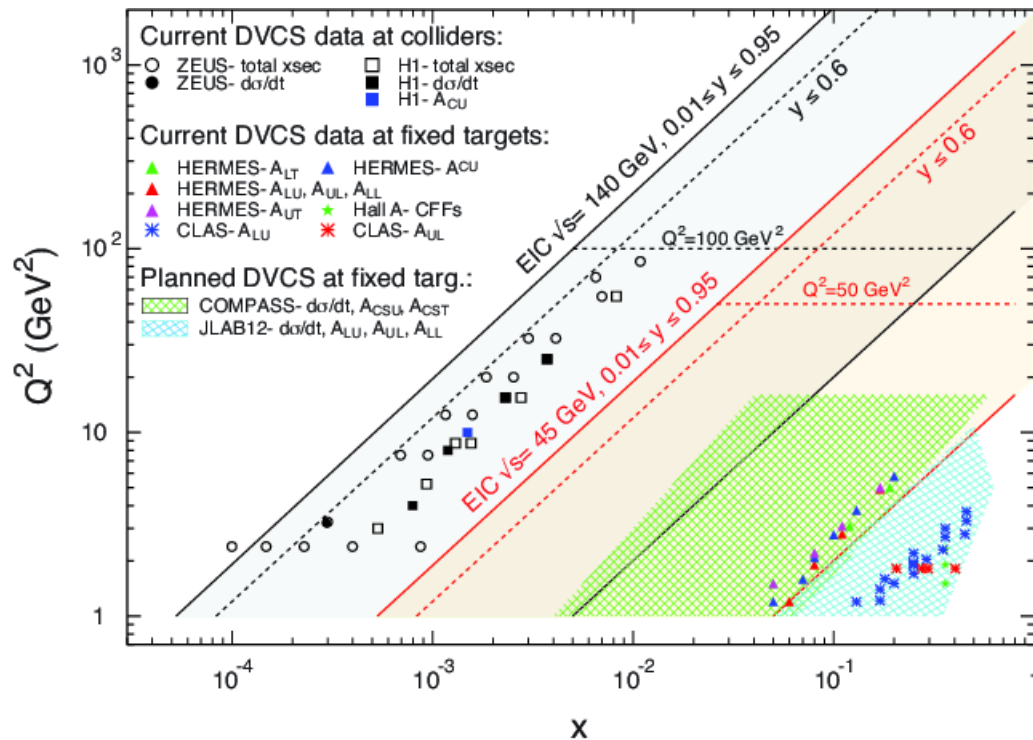
Resolution scale Q^2



$M^2 + Q^2$

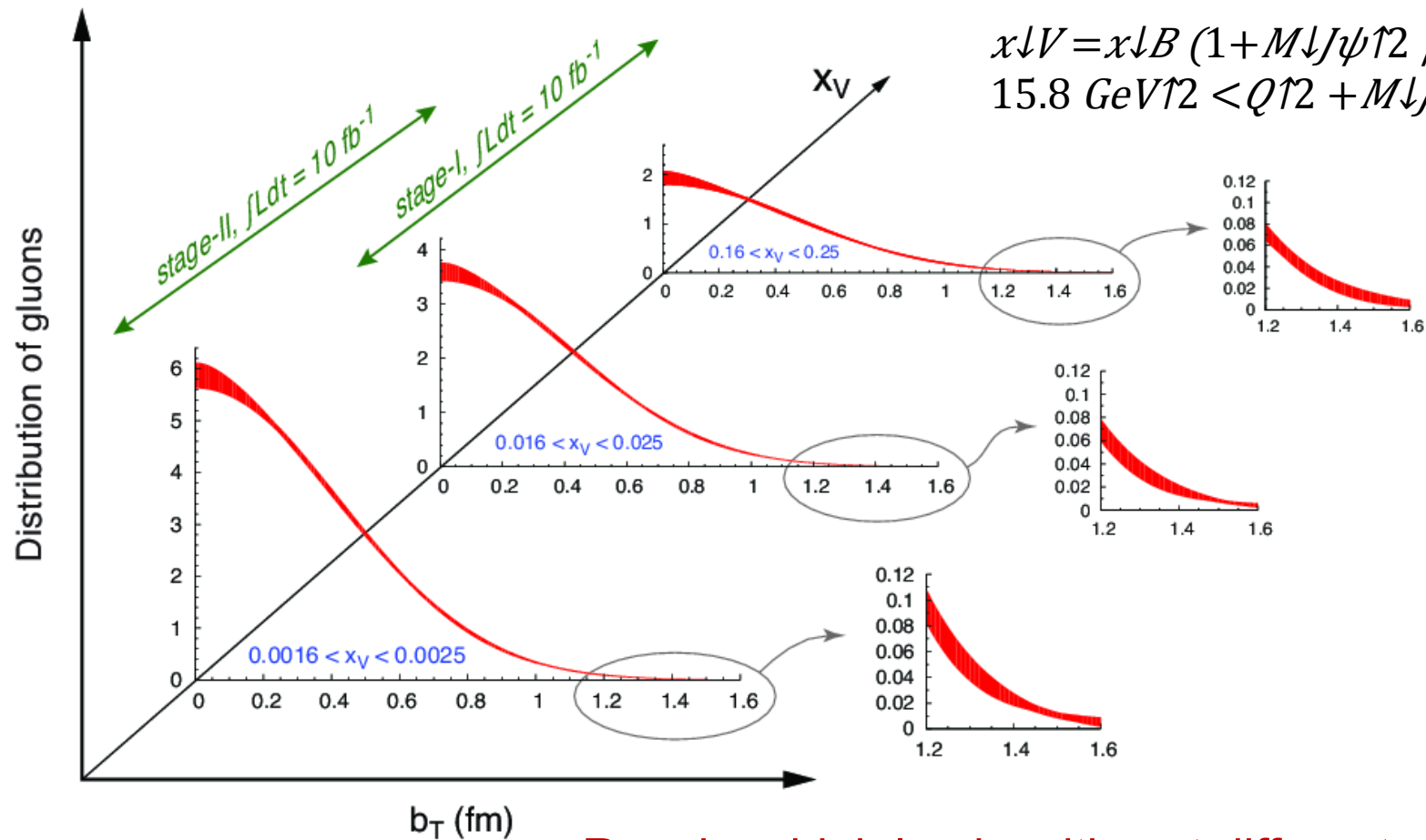
Deeply Virtual Compton Scattering

Limited and mainly unpolarized data at low- x



For spatial imaging measure $d\sigma/dt$
Need binning in $x \downarrow B$ and $Q^2 \downarrow$

Gluon Distributions



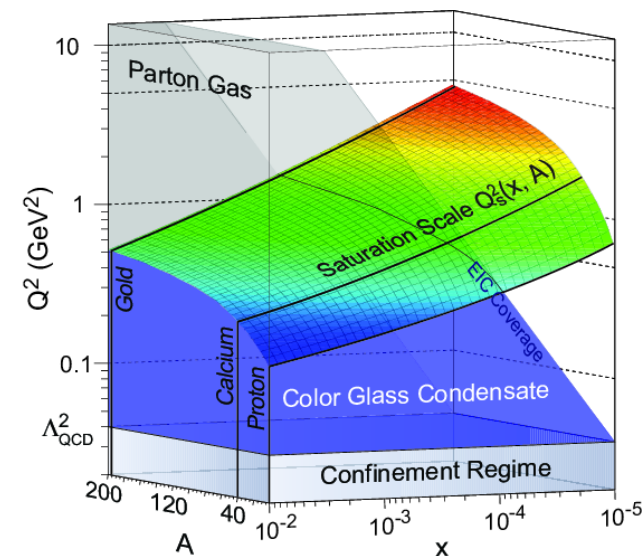
$$x_V = x_B (1 + M_{J/\psi}^2 / Q^2)$$

$$15.8 \text{ GeV}^2 < Q^2 + M_{J/\psi}^2 < 25.1 \text{ GeV}^2$$

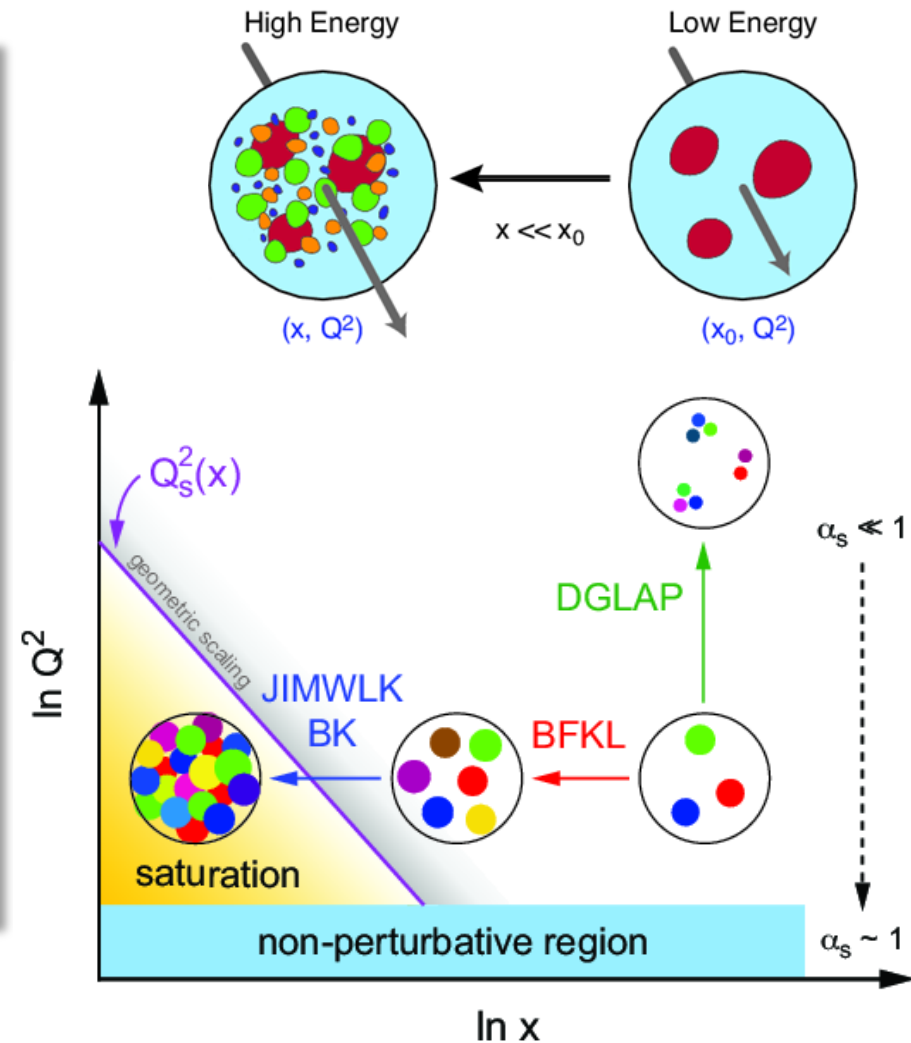
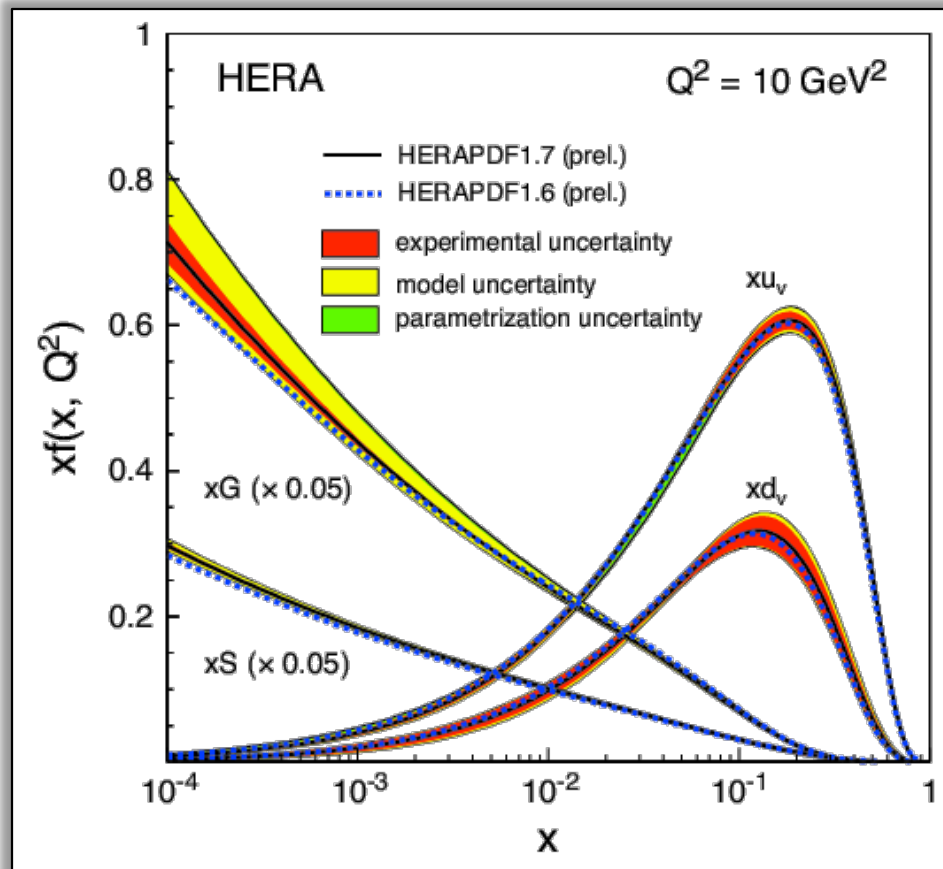
Requires high luminosities at different energies to map out the spatial distribution

The Nucleus: A Laboratory for QCD

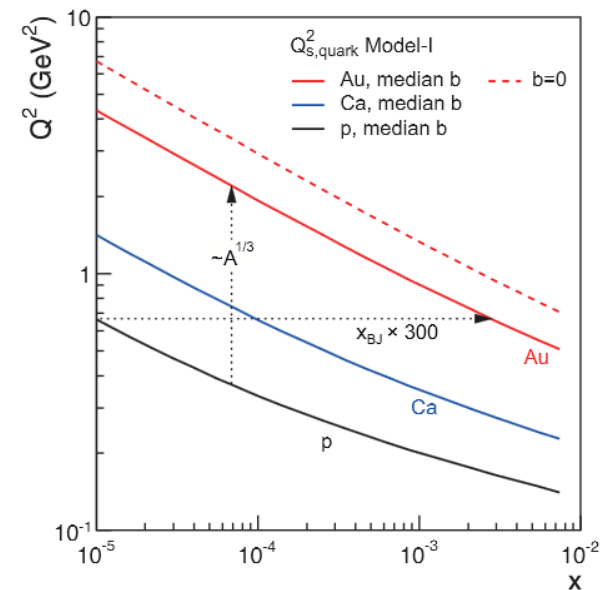
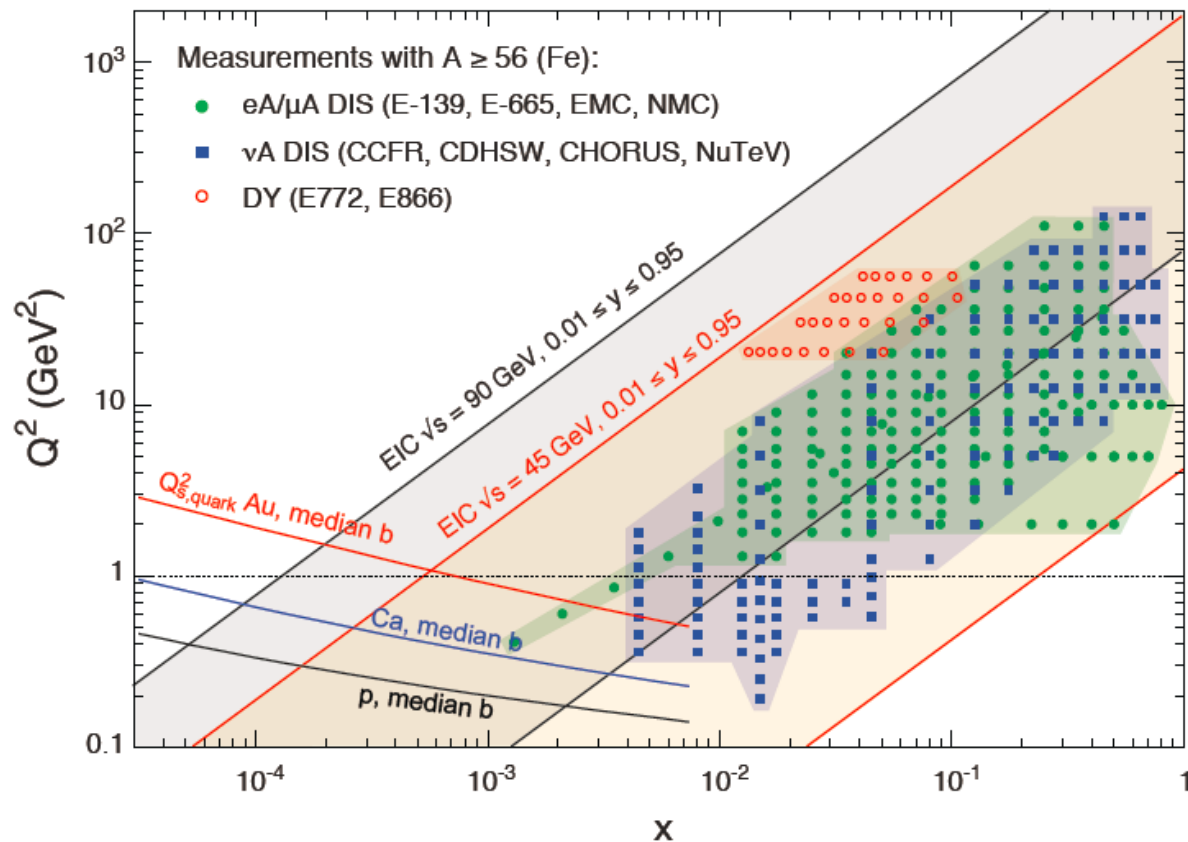
- What is the role of strong gluon fields, parton saturation effects, and collective gluon excitations in nuclei?
- Can we experimentally find evidence of non-linear QCD dynamics in the high-energy scattering off nuclei?
- What are the momentum/spatial distributions of gluons and sea quarks in nuclei?
- Are there strong color fluctuations inside a large nucleus?



High Gluon Densities in Nuclei



Lepton-Nucleus Scattering



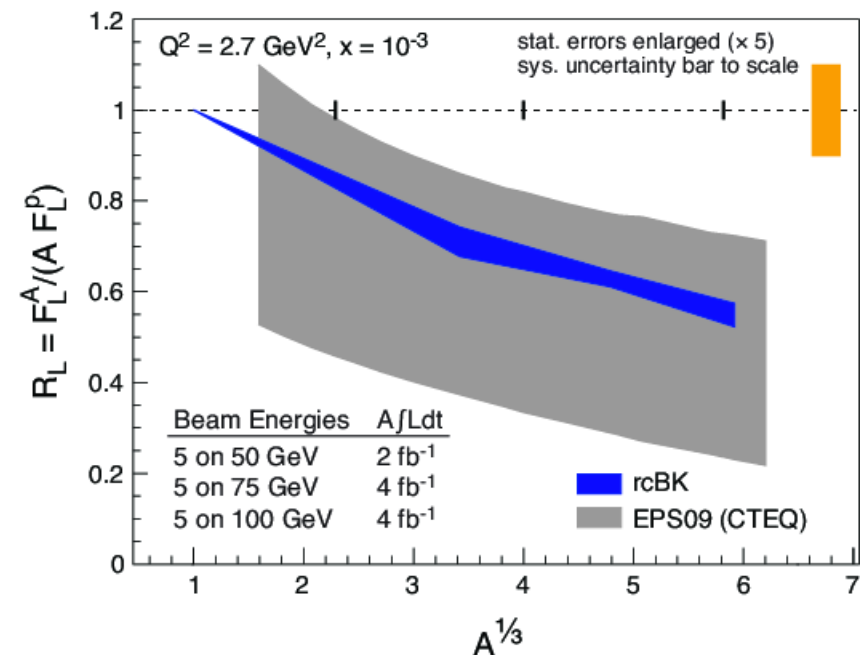
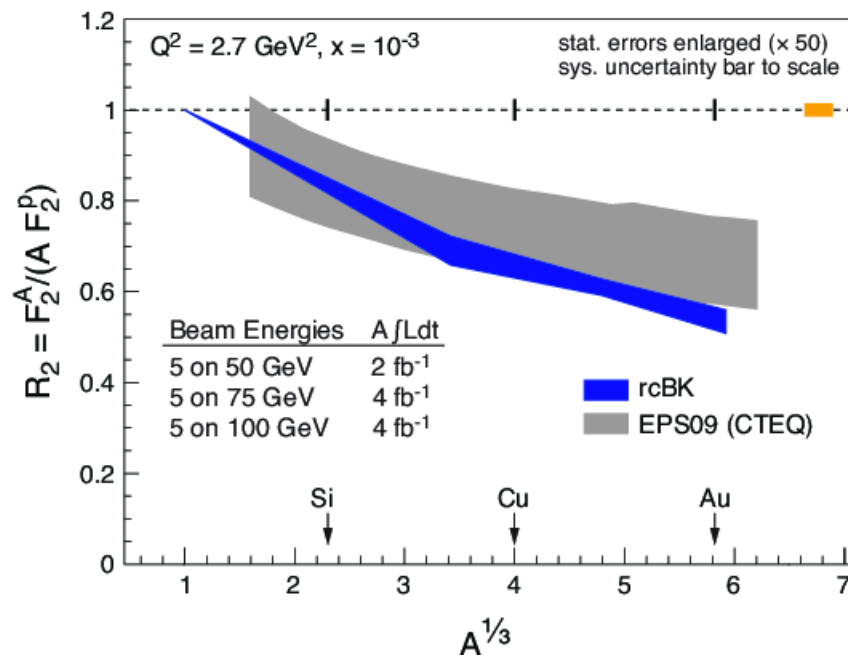
u.r. boost amplifies the gluon densities in nucleus ($R \sim A^{1/3}$)

$$Q^2 \downarrow \rightarrow f_2(x) \sim (A/x)^{1/3}$$

Parton distributions in a nucleus are not a simple superposition of nucleons

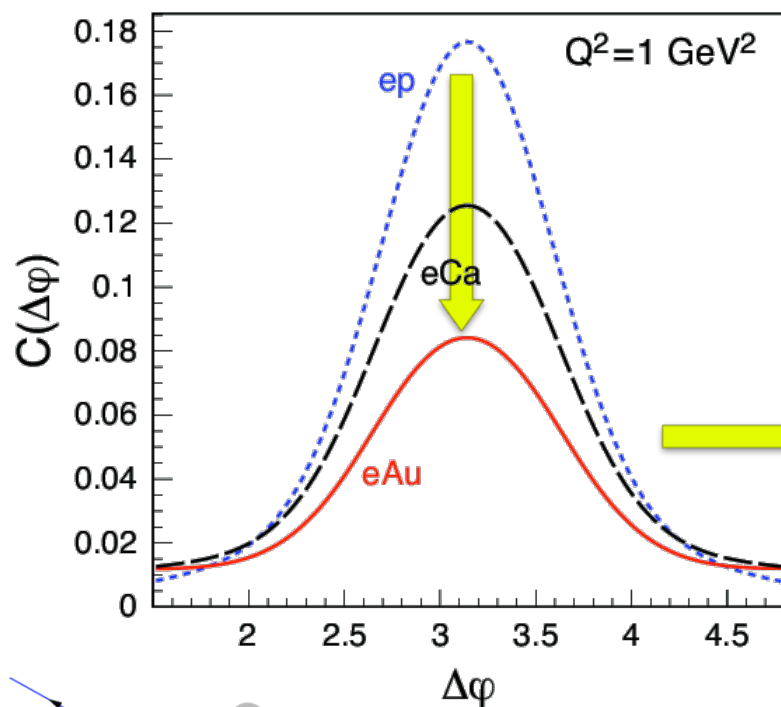
Nuclear PDFs

- Expect strong non-linear effects in F_L from higher twist contributions
 - Dipole model from Bartels et al.
- Quantify by $R_{2/L}(x, Q^2) = F_{2/L}^A(x, Q^2) / A \cdot F_{2/L}^p(x, Q^2)$

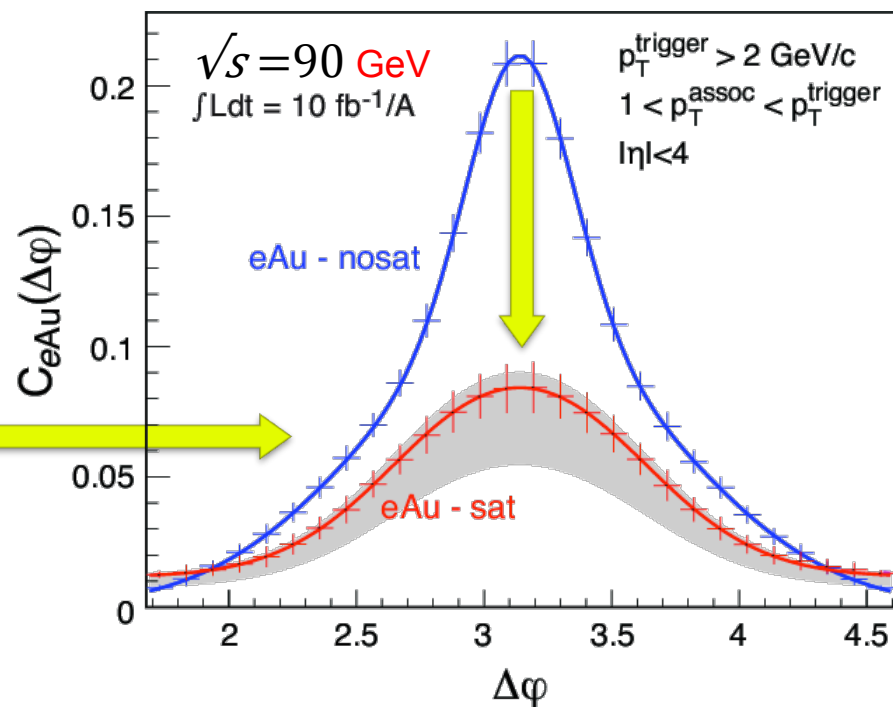


Di-hadron Correlations

Prediction in CGC framework



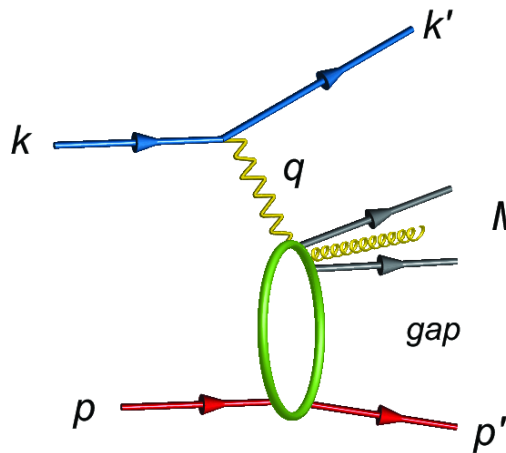
Expected experimental significance



with EPS09 (nPDF shadowing)
 PYTHIA6 (partons, showers, fragmentation)
 DPMJet-III (nuclear geometry)

PRD 83, 1 5005 (2011), PRL 106, 022301 (2011)

Diffractive Scattering



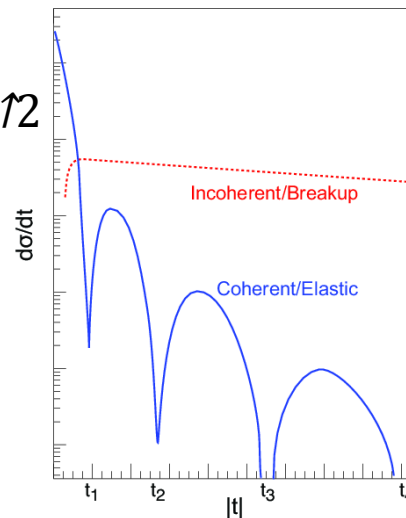
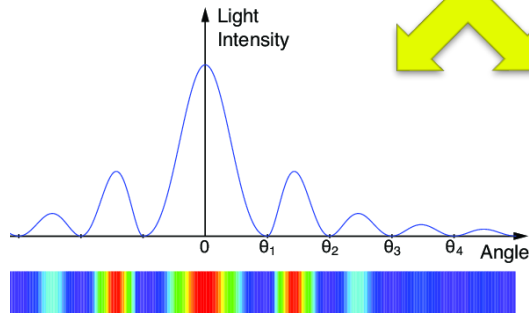
$$t = (p - p')^2$$

$$M_X^2 = (p - p' + k - k')^2$$

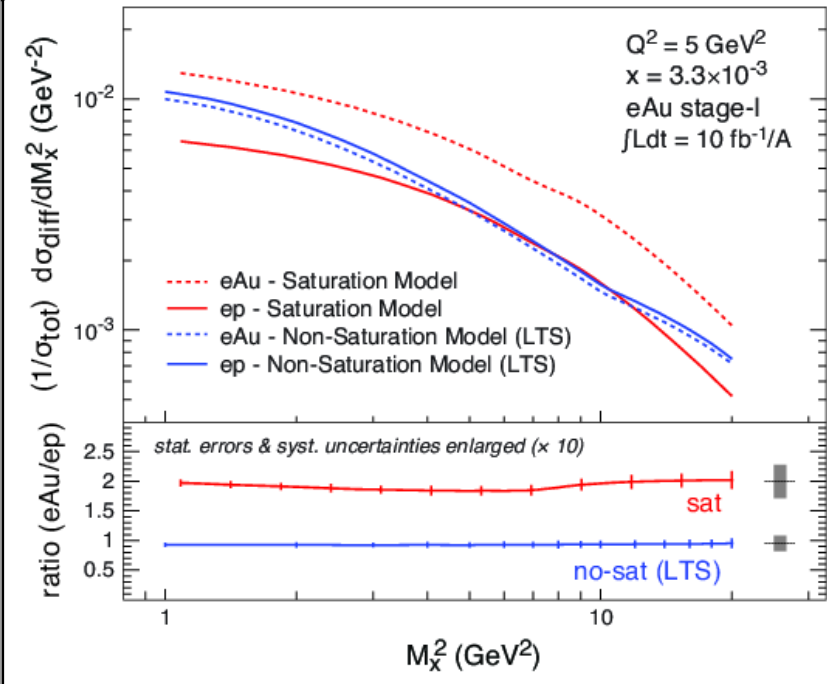
M_X Rapidity gap

$$\eta = -1/2 \ln(\tan \theta/2)$$

$$|t| \approx k^2 \theta^2$$

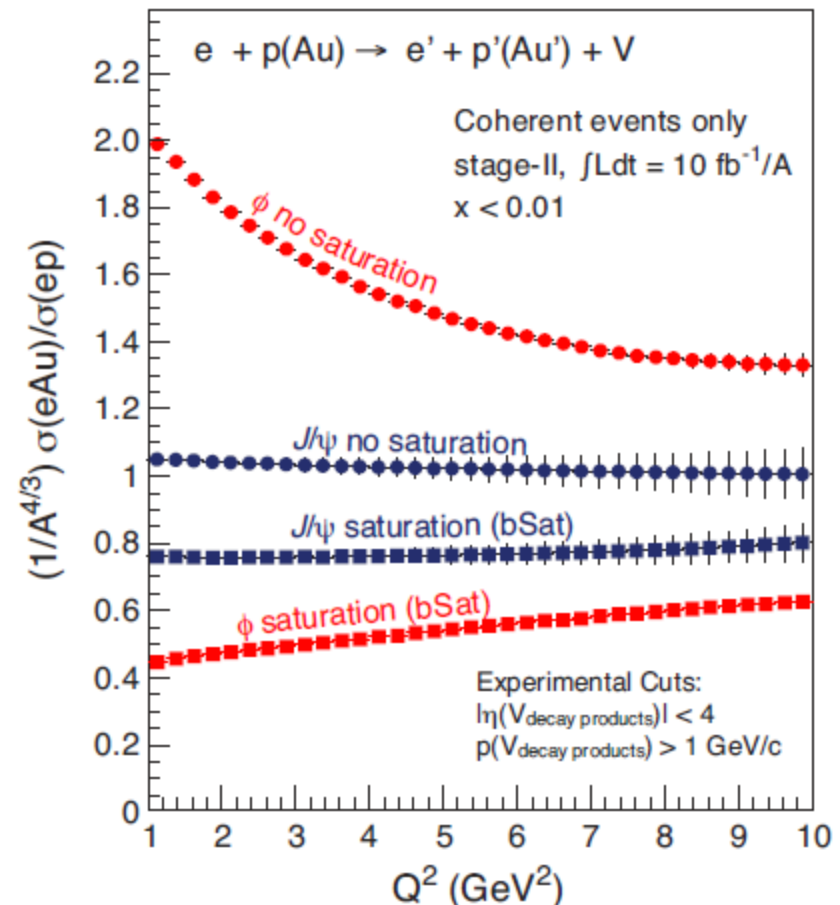
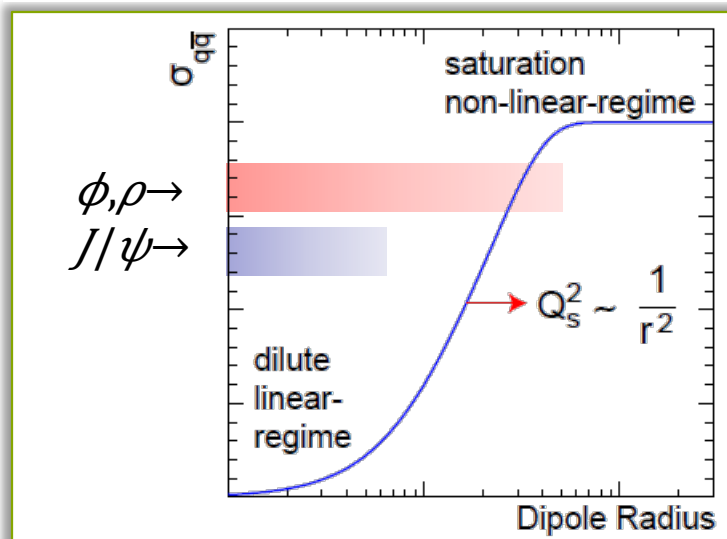
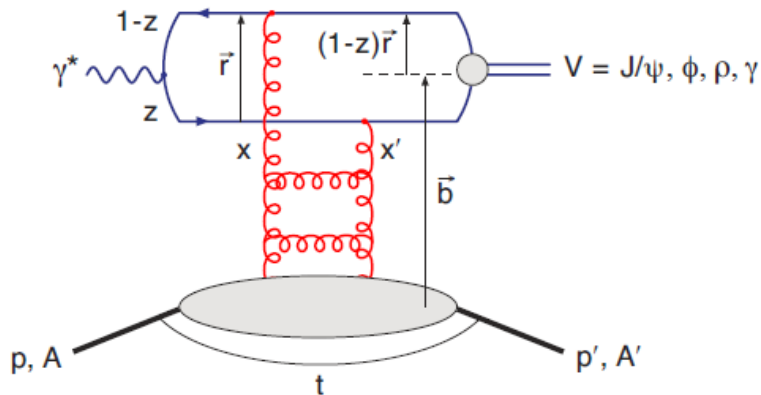


Black disc limit $\sigma_{diff} / \sigma_{tot} = 0.5$
Non-linear effects amplify σ_{diff} in e+A

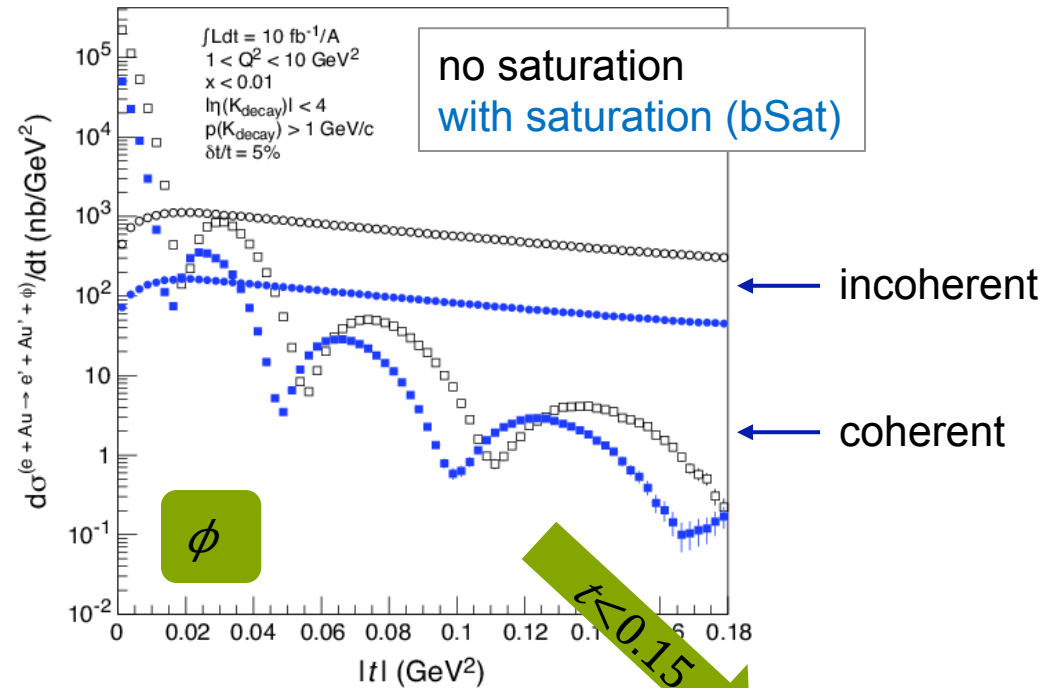
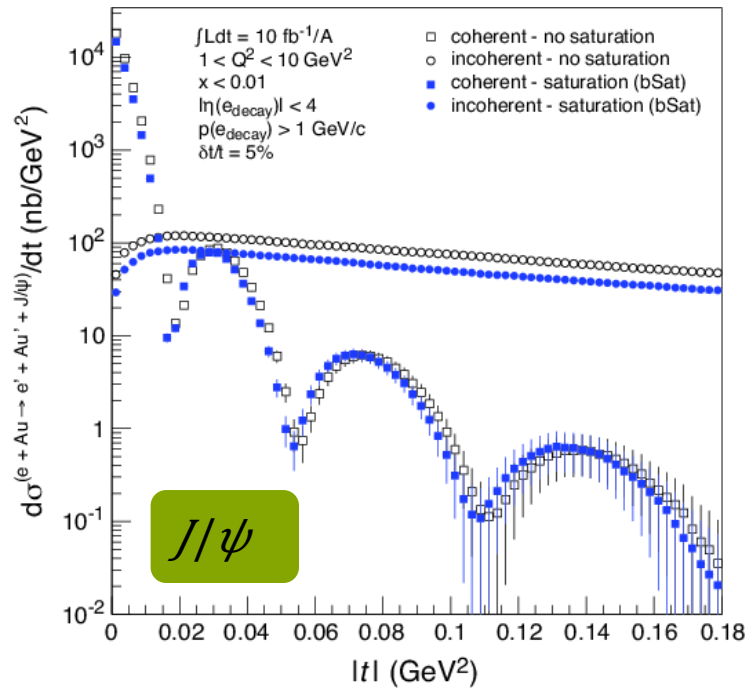


Exclusive Vector Meson Production

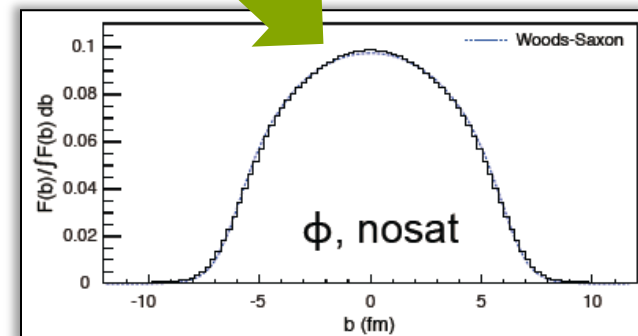
Fix momentum transfer $t = (p \downarrow A - p \downarrow A')^2 = (p \downarrow VM + p \downarrow e' - p \downarrow e)^2$



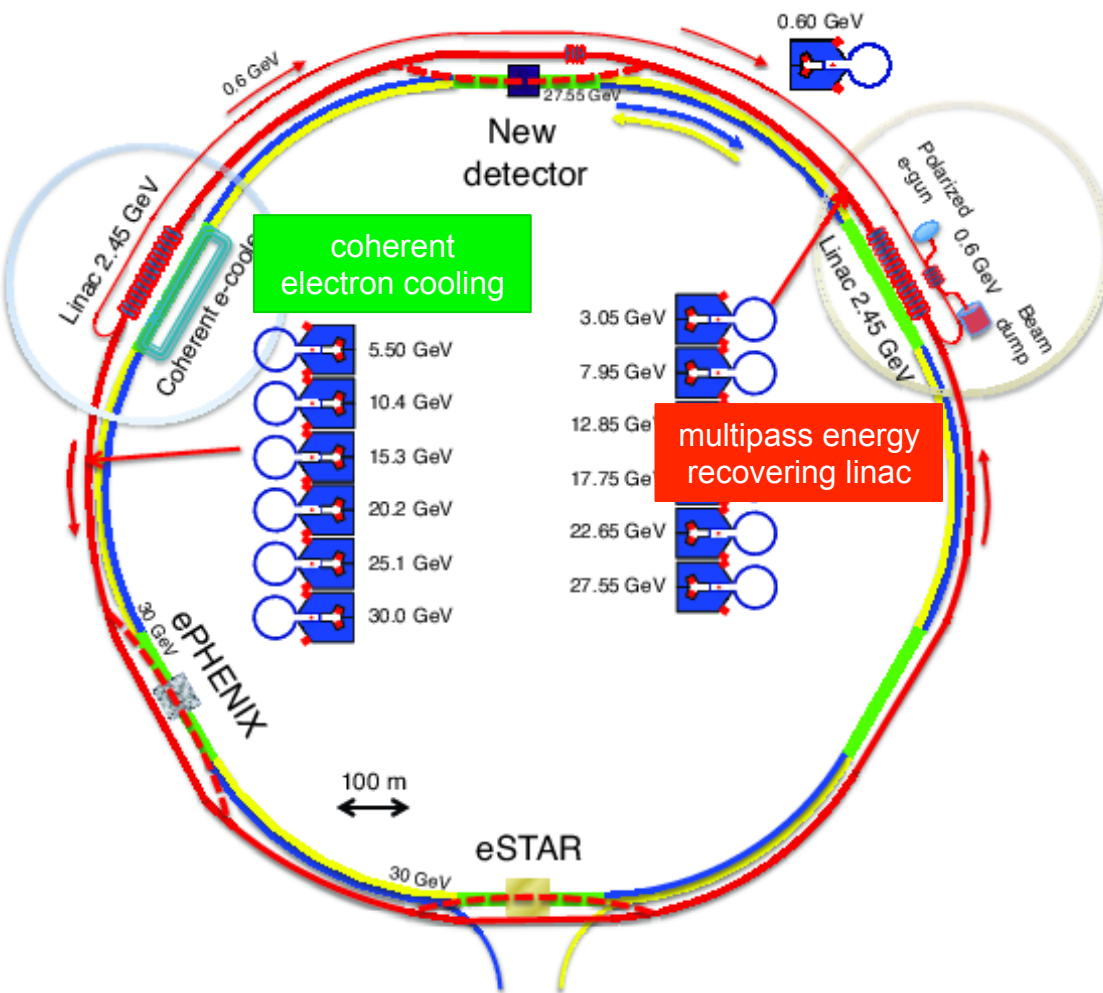
Spatial Gluon Distribution



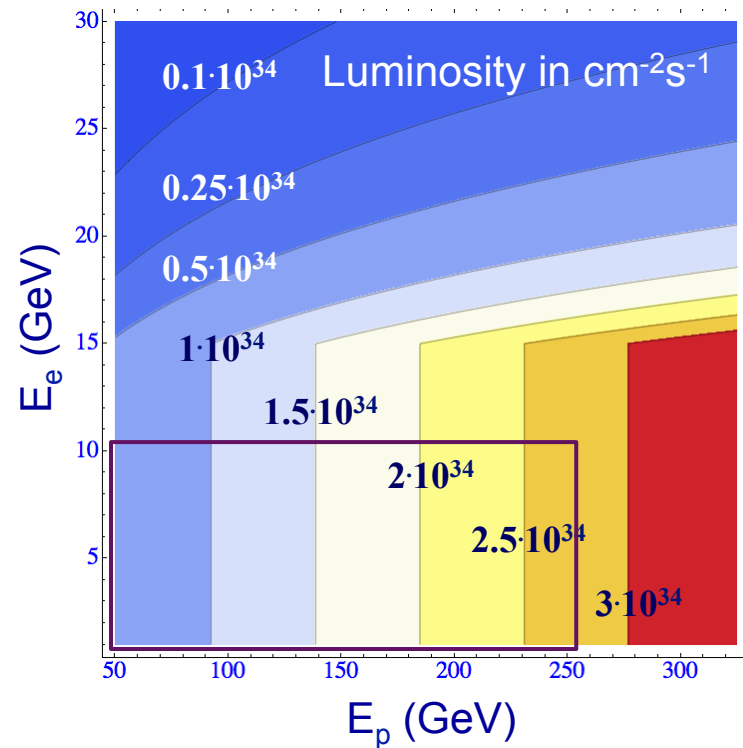
- Coherent part probes “black disc”
 - Fourier transform $t \rightarrow b_T$
- Incoherent part probes lumpiness of the source



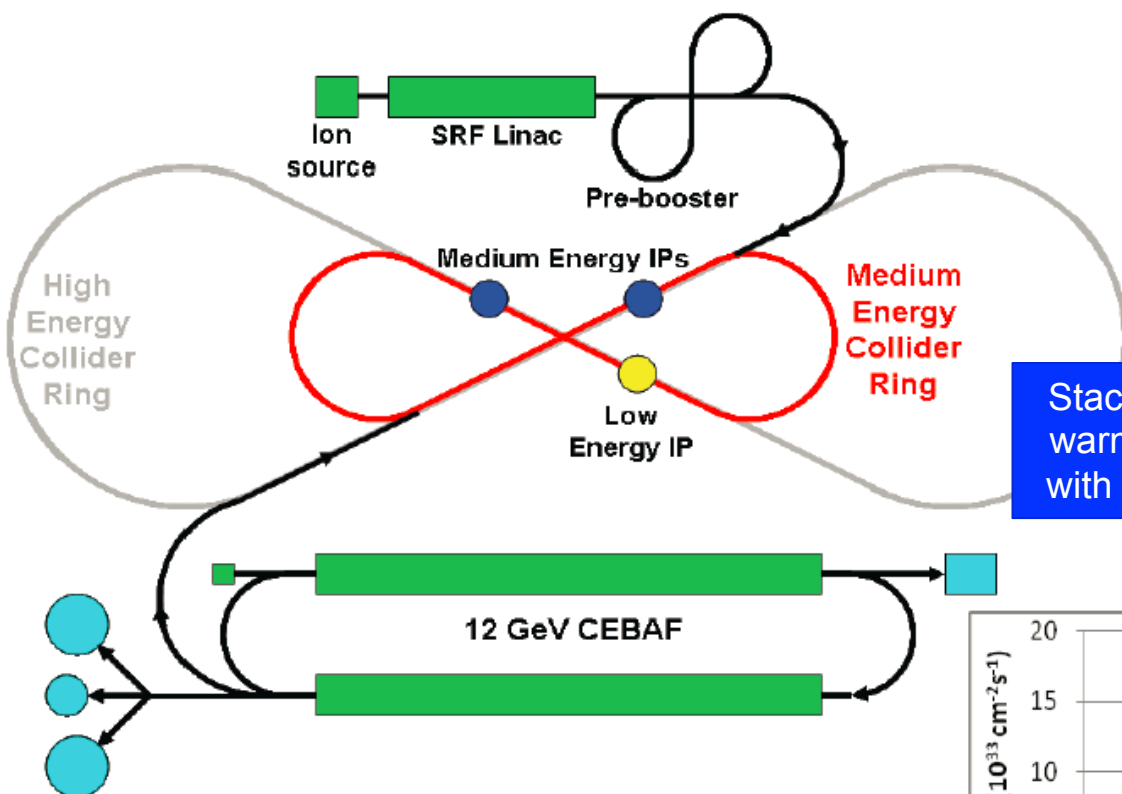
ERL eRHIC



Electron beam energy	10 GeV
Proton beam energy	250 GeV
Ion beam energy	100 GeV/u
Electron beam polarization	80%
Proton beam polarization	70%

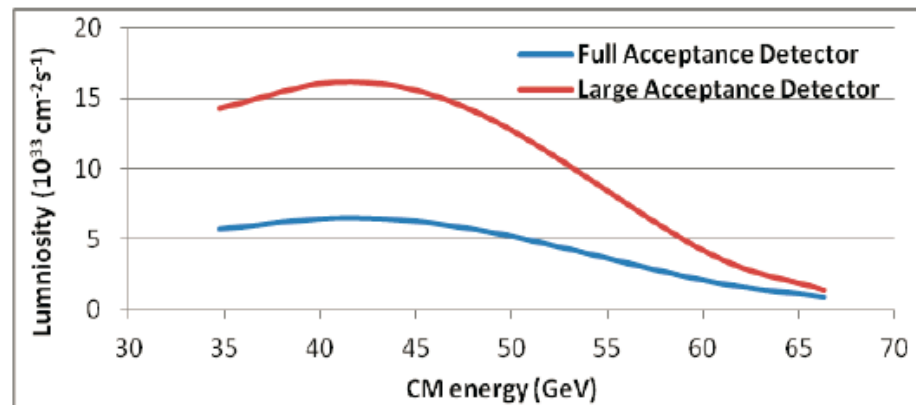


MEIC

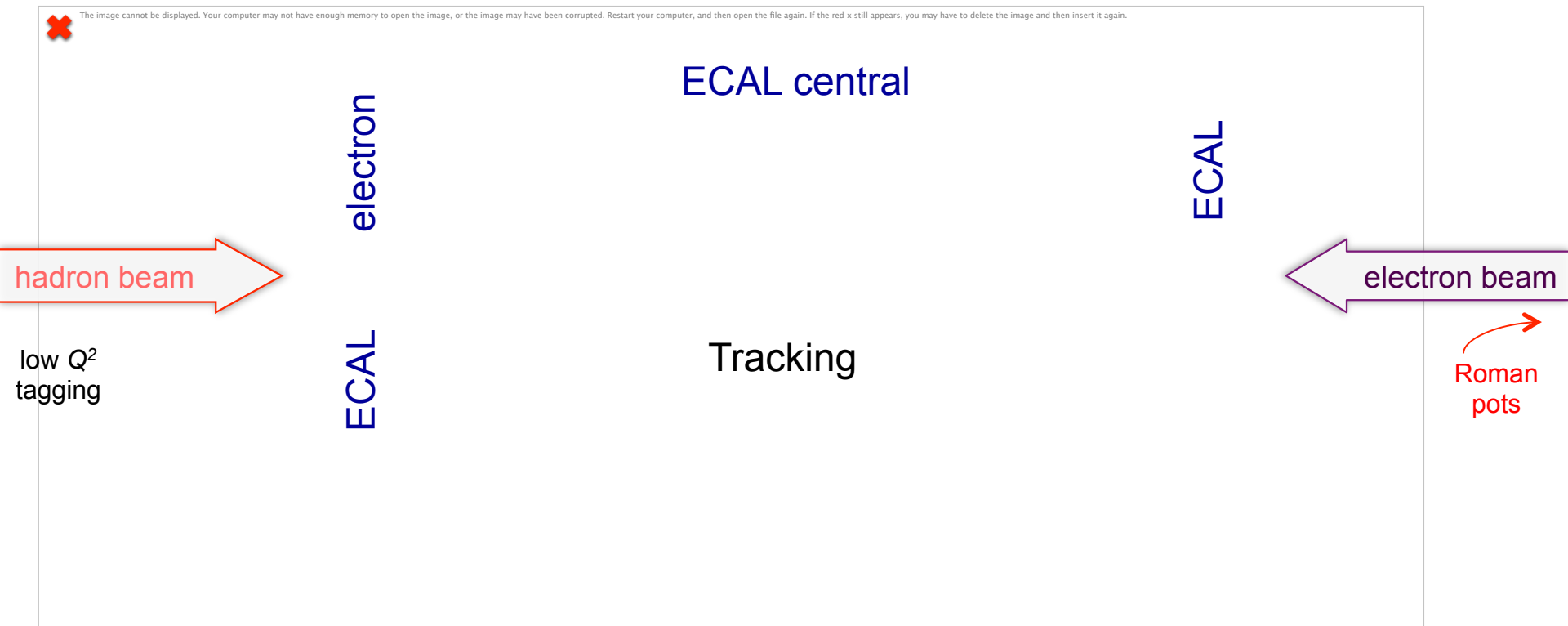


Electron beam energy	5 GeV
Proton beam energy	100 GeV
Ion beam energy	40 GeV/u
Electron beam polarization	80%
Proton beam polarization	70%

Stacks electron rings and warm low energy booster with cold high energy ring



1st Detector Concept



Interaction region has to be integrated in the accelerator design

Particle identification and resolution requirements from inclusive, semi-inclusive, and exclusive measurements

Acceptance for different collision systems and energies

Future Opportunities at an EIC...

...will lead to the most comprehensive picture of the nucleon with flavor, spin, and spatial structure.

...will enable unprecedented studies of non-linear effects in QCD at extreme parton densities and the propagation/interaction of color charges in nuclei.

The EIC will combine polarized $e+p$ collisions with ion beams from light to heavy nuclei at the highest luminosities at center-of-mass energies up to 150 GeV.

The physics goals require extreme kinematic coverage and state-of-the-art technologies for a dedicated detector.



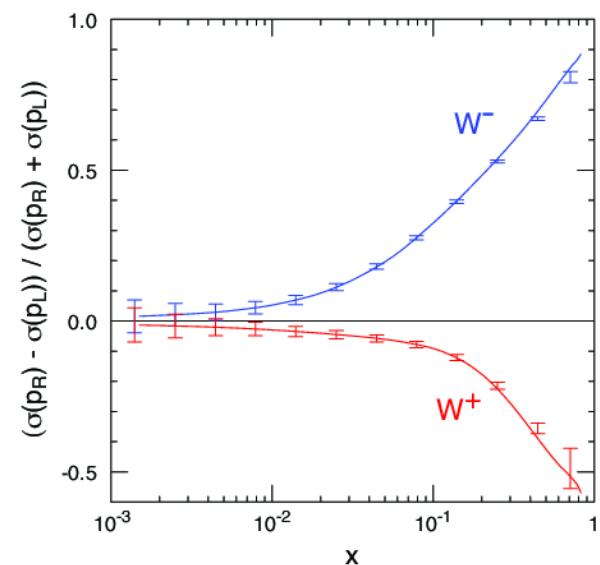
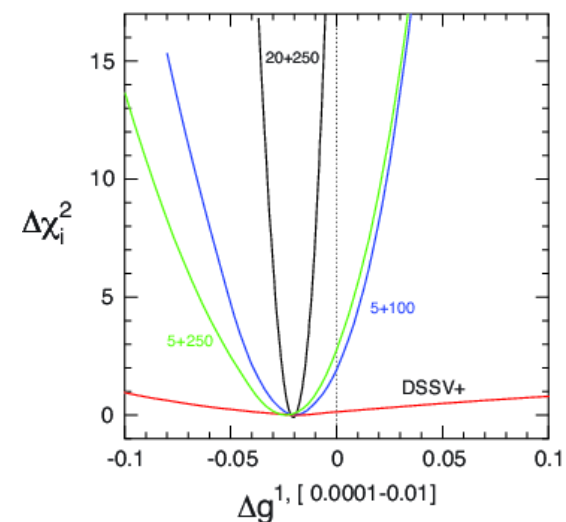
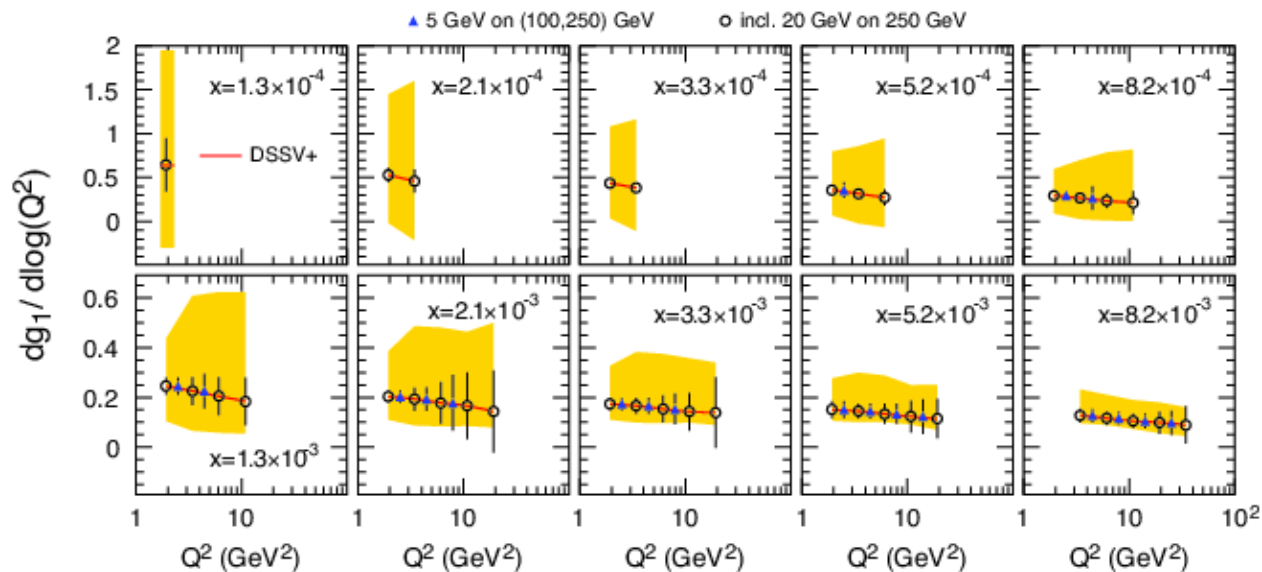
Electron Ion Collider: The Next QCD Frontier

Understanding the glue
that binds us all

arXiv:1212.1701

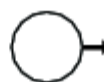
http://www.bnl.gov/npp/docs/EIC_White_Paper_Final.pdf

Longitudinal Spin Structure



Transverse Momentum Dependence

Leading Twist TMDs



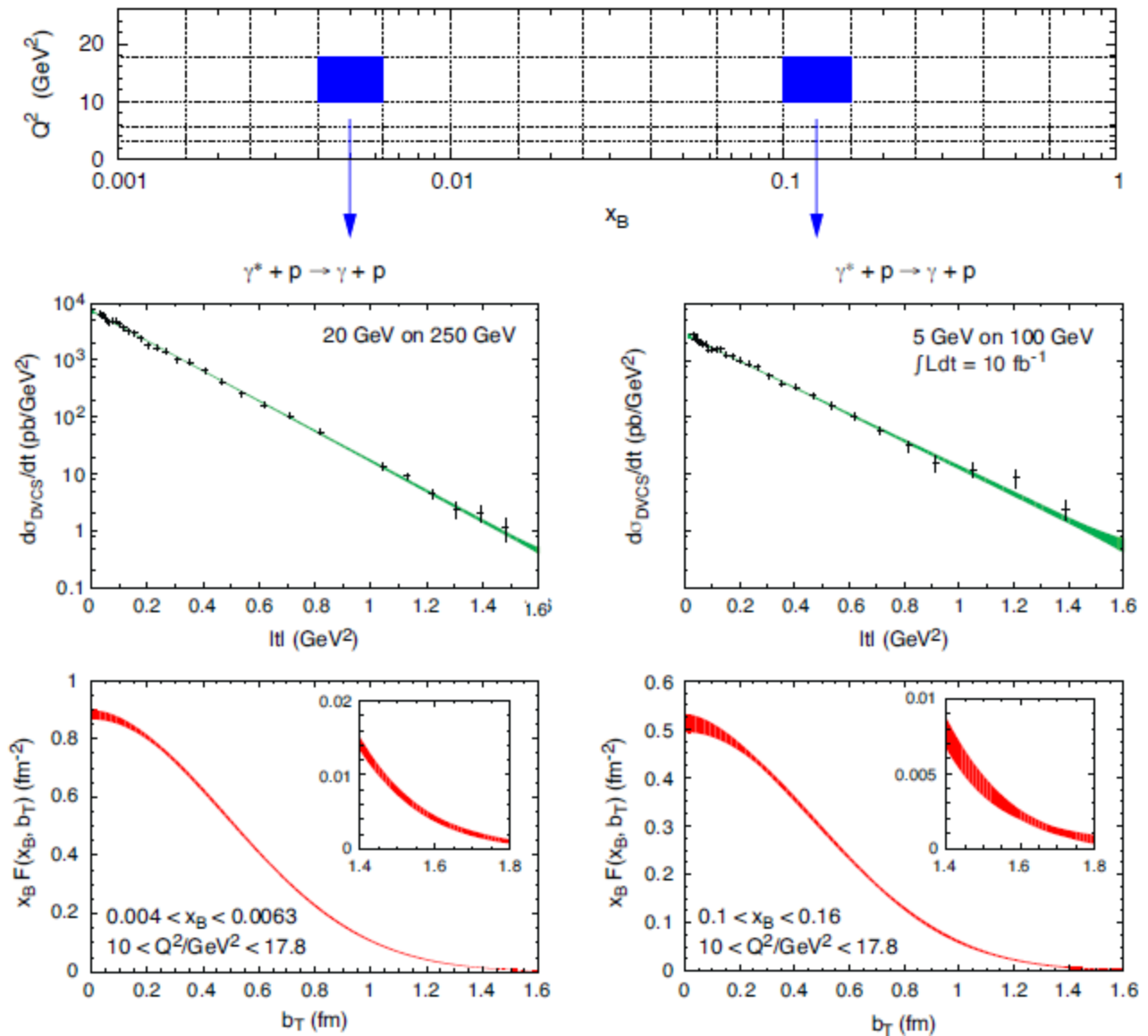
Nucleon Spin



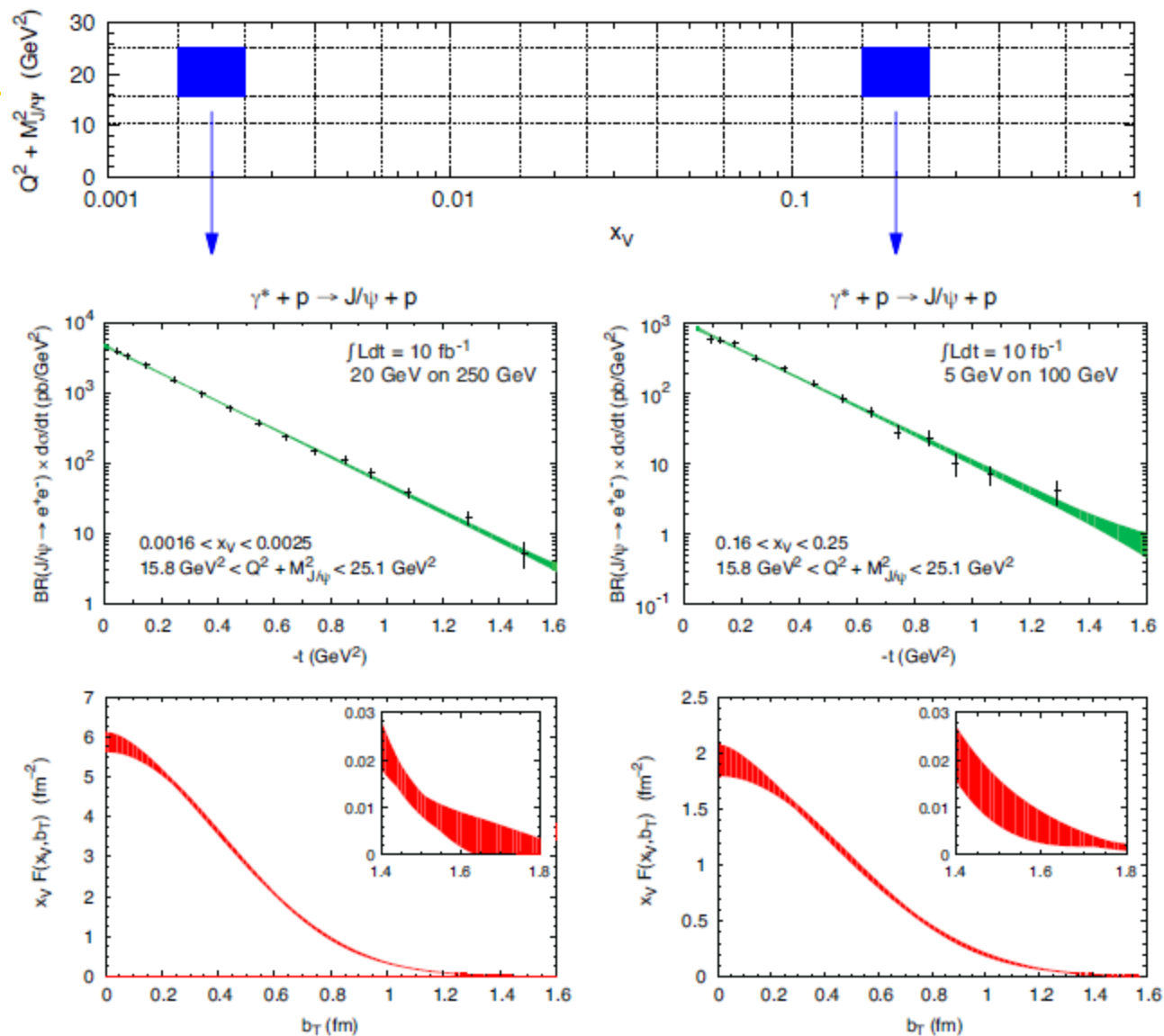
Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ — Boer-Mulders
	L		$g_{1L} =$ — Helicity	$h_{1L}^\perp =$ —
	T	$f_{1T}^\perp =$ — Sivers	$g_{1T}^\perp =$ —	$h_1 =$ — Transversity $h_{1T}^\perp =$ —

DVCS



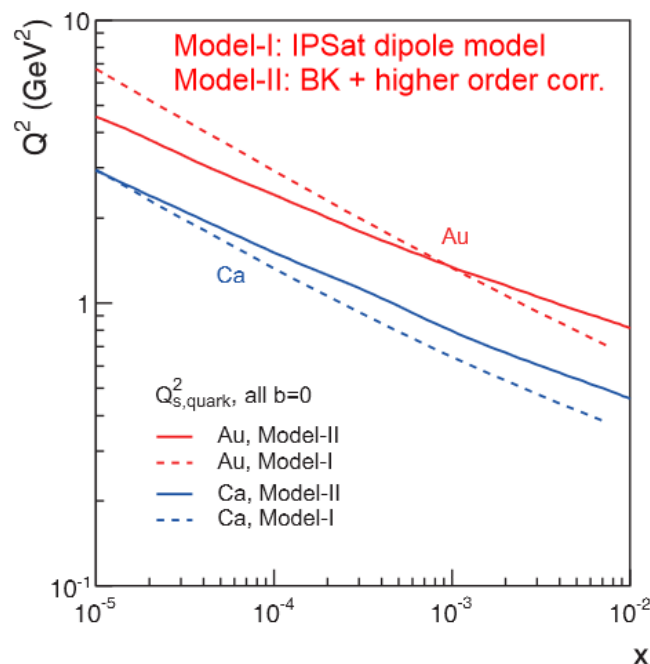
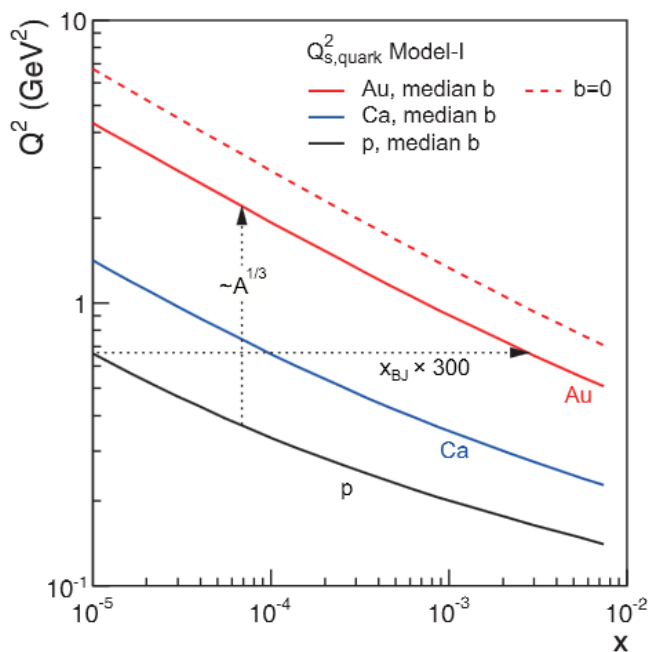
VM



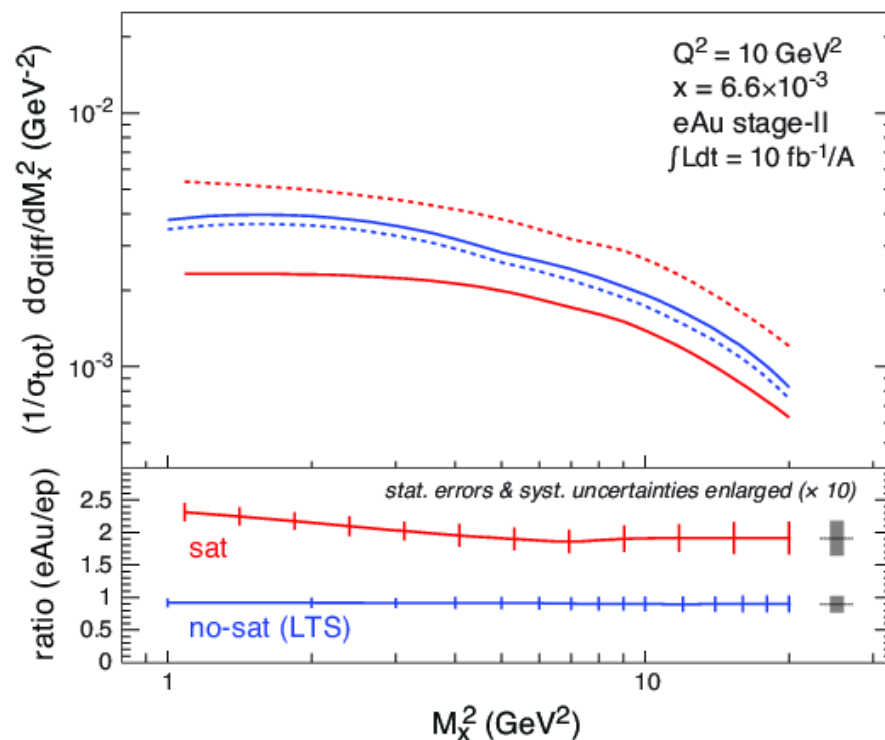
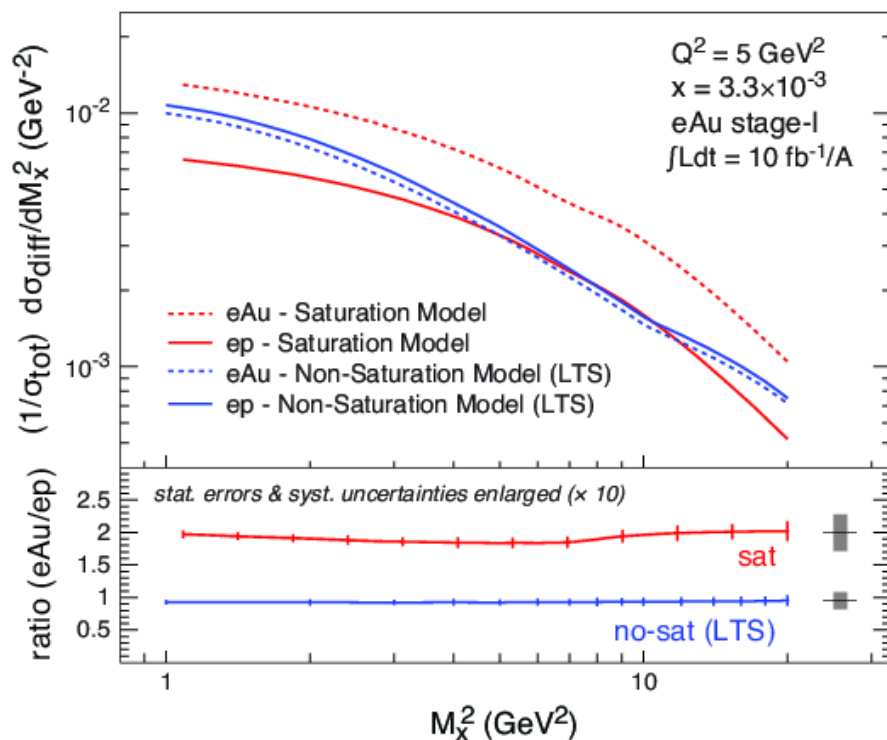
Saturation Scale Q_s

The ultra-relativistic boost amplifies the gluon densities in a nucleus $R \sim A^{1/3}$

$$Q_s^2(x) \sim (A/x)^{1/3}$$



Diffractive Cross Section



DIS Kinematics

Scattered electron

$$Q^2 > 1 \text{ GeV}^2$$

$$0.01 < y < 0.95$$

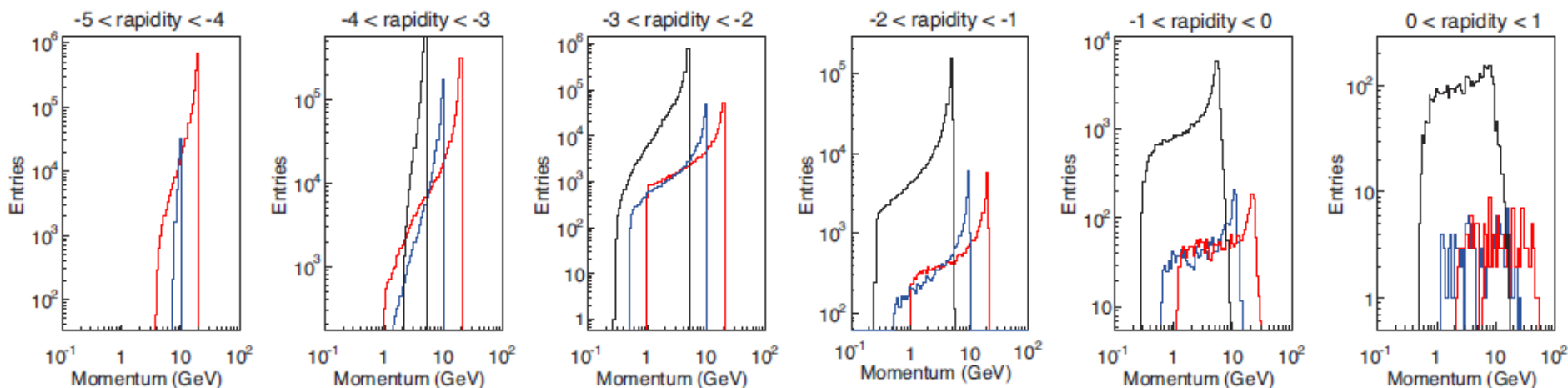
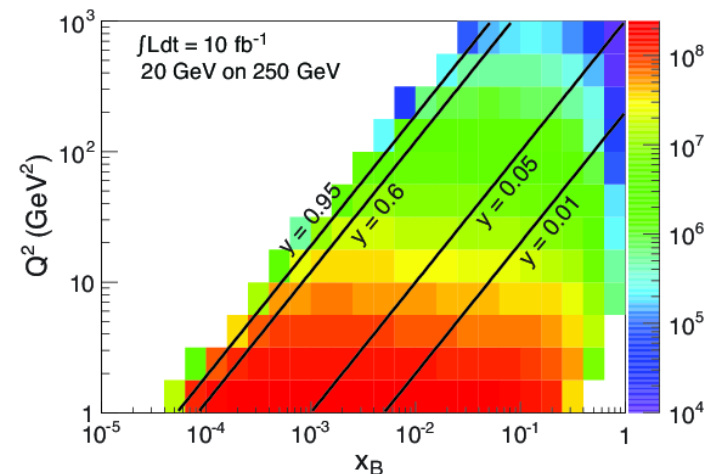
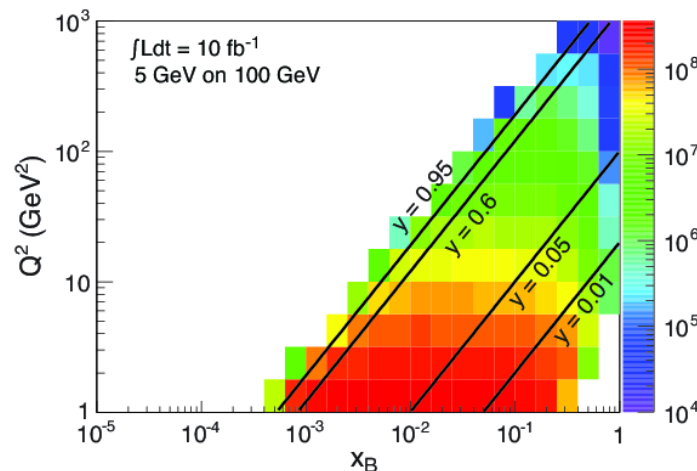
$$0.1 < z$$

$$-5 < \eta < 5$$

5 GeV x 50 GeV

10 GeV x 100 GeV

20 GeV x 250 GeV



SIDIS Kinematics

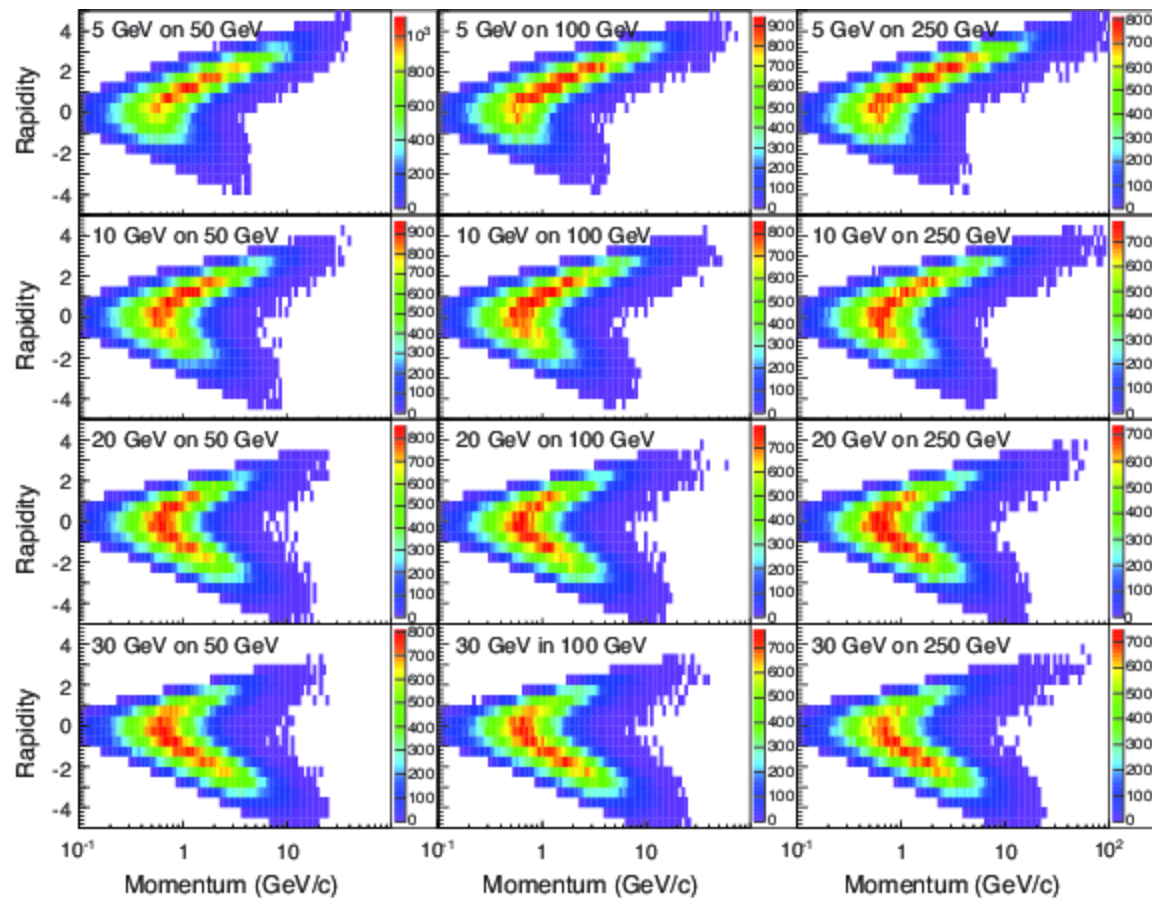
Non-exclusive pion

$$Q^2 > 1 \text{ GeV}^2$$

$$0.01 < y < 0.95$$

$$0.1 < z$$

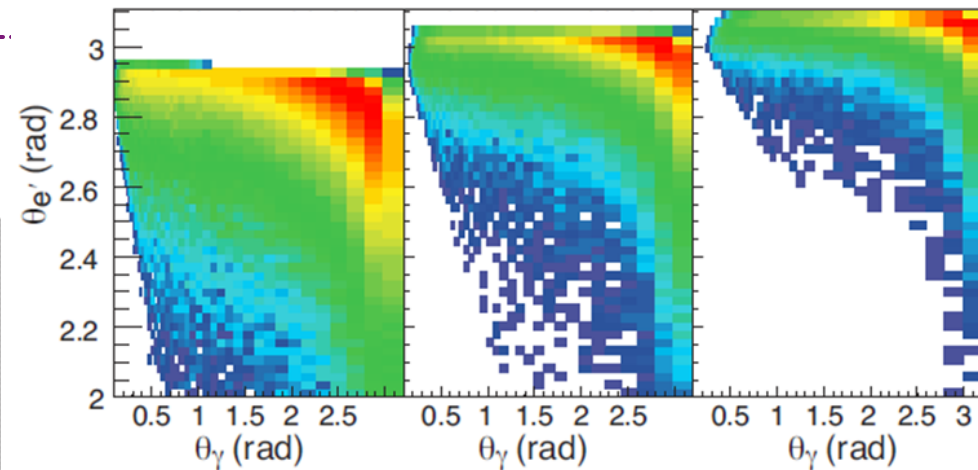
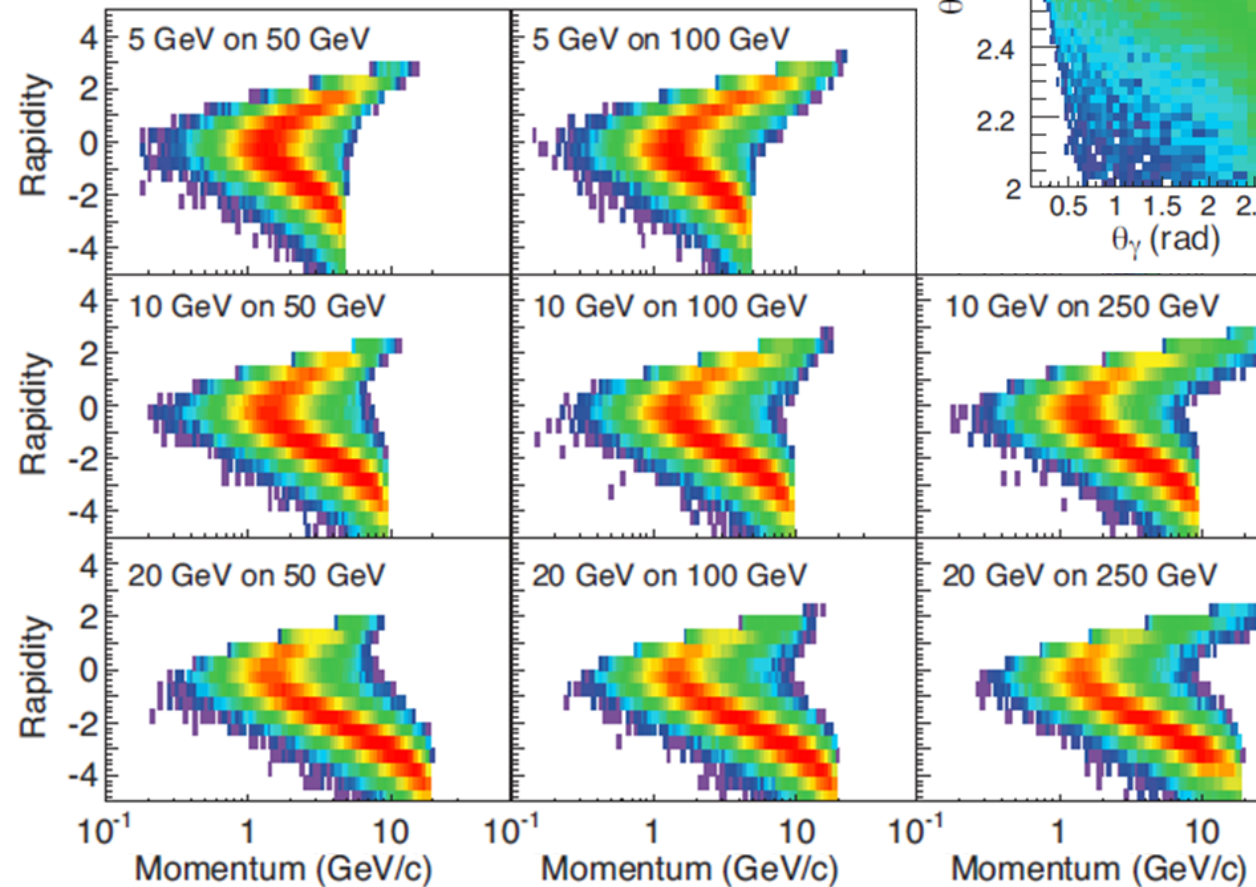
$$-5 < \eta < 5$$



DVCS Kinematics

5 GeV x 100 GeV 10 GeV x 100 GeV 20 GeV x 100 GeV

Photon in lab. frame



Precision Measurement of $\sin^2 \theta_W$

$\theta_W \uparrow$ $\theta_W \downarrow$ $\theta_W \uparrow$ $\theta_W \downarrow$

